BEYOND THE STANDARD MODEL WITH ASTROPHYSICS AT ALL WAVELENGTHS

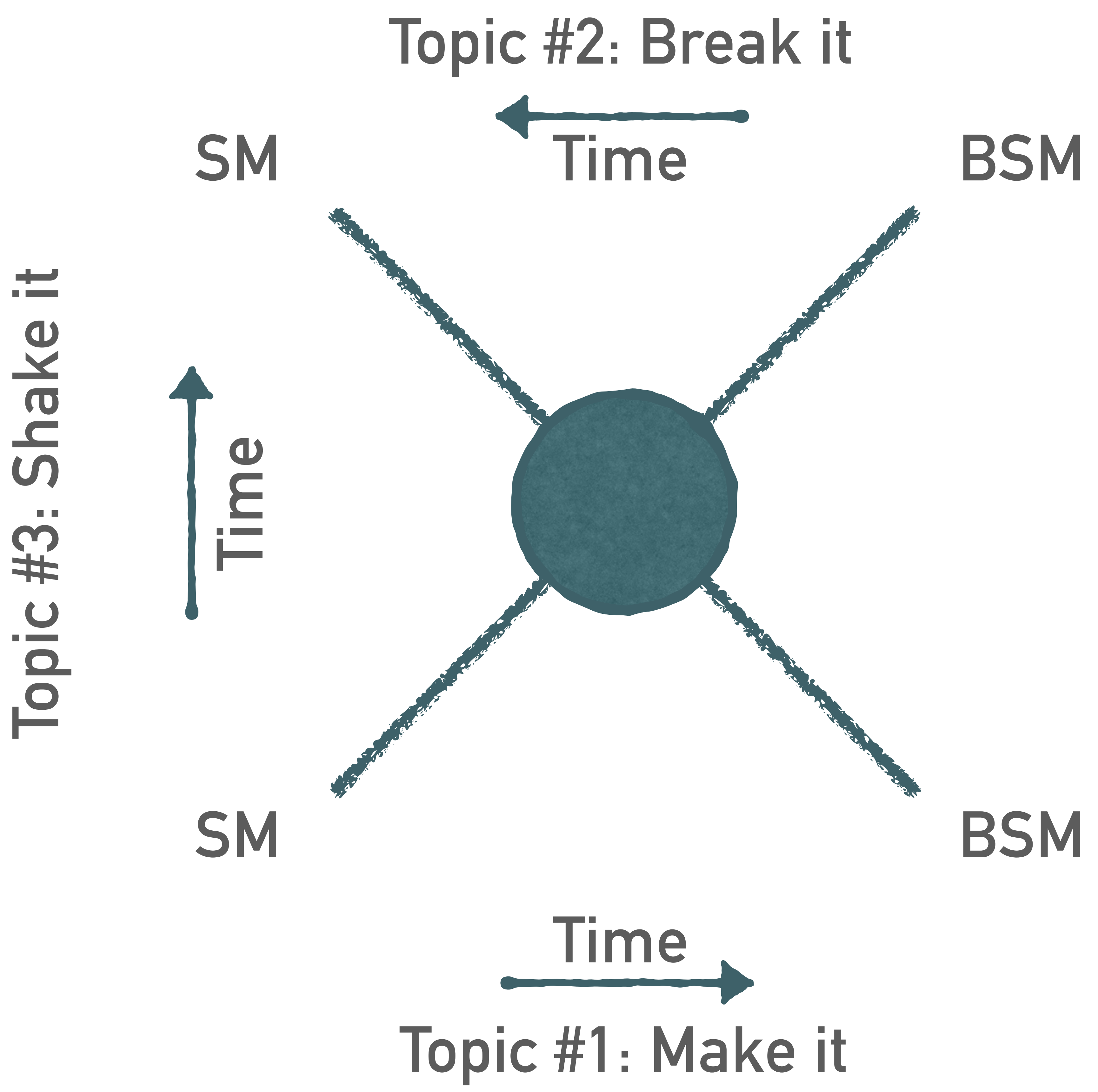
Katelin Schutz, McGill University

UNDARK School 2026

MY MISSION STATEMENT FOR THESE LECTURES

- This is a huge topic! It won't be possible to do anything comprehensive, so I have tried to curate a selection that highlights the *diversity* of different astrophysical probes that we can use to constrain a very broad variety of models of BSM physics
- Astrophysical observations are usually probing lower energy levels than what's accessible in terrestrial experiments (major exception: neutrinos!) so I will often embrace a bottom-up EFT approach and think about different dimension four "portals" to BSM physics
- In light of the above, I want to cover ground quickly so we will do things order-of-magnitude style, in other words $3 = \pi = 10$ and I won't commit to any factors of 2
- Similarly, lots of spherical cows everywhere, my goal is to get you thinking about the concepts and to know where to look if you want to follow things up more in detail
- Let's have fun with it!

BROAD OUTLINE OF THE LECTURES



Different modes of contact
(including gravitational) with the SM

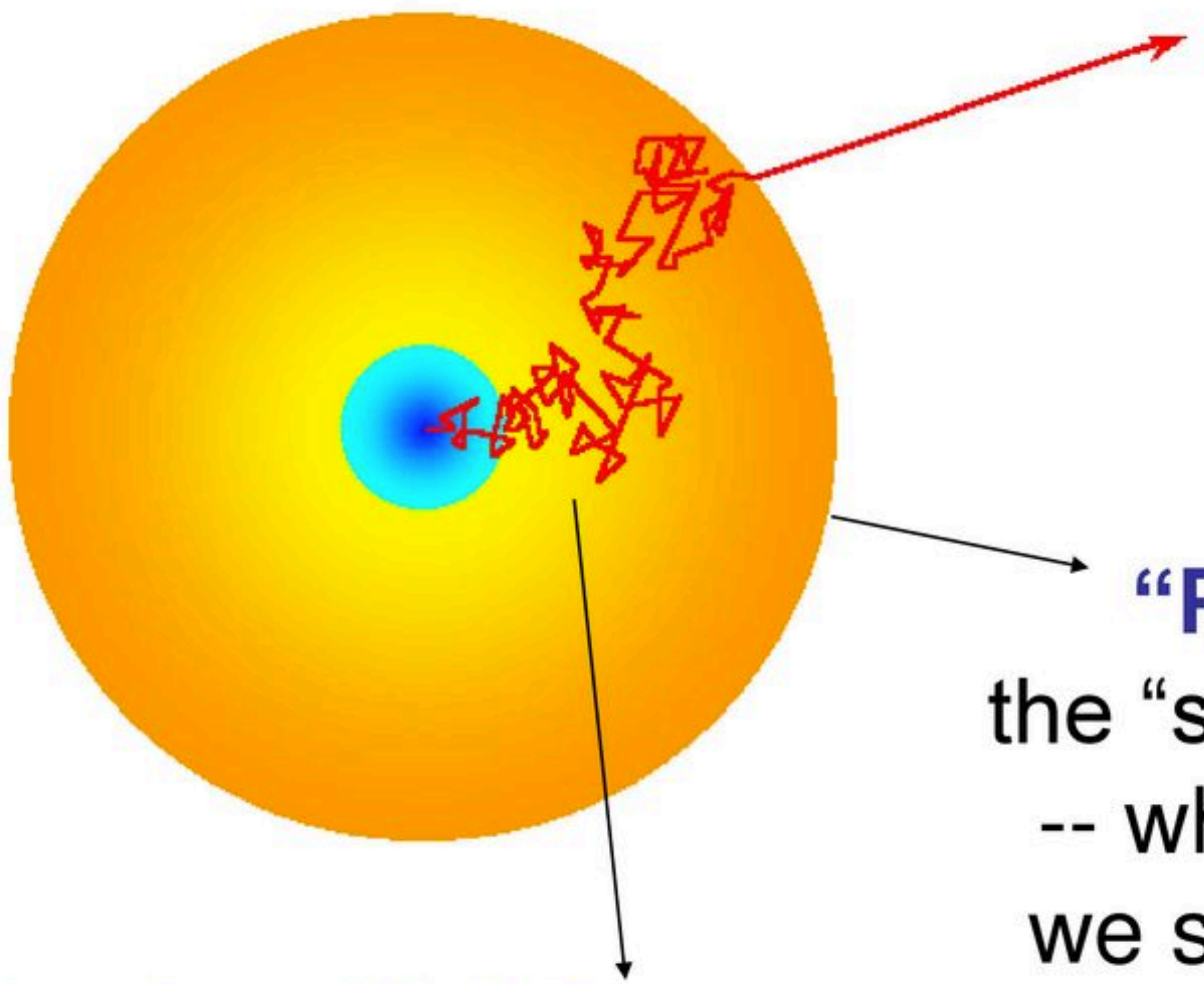
TOPIC #1: MAKE IT

TOPIC #1: MAKE IT

MODEL SYSTEM: STARS AND COMPACT OBJECTS

Key references: Raffelt "Stars as Laboratories for Fundamental Physics"
Maoz "Astrophysics in a Nutshell"

PHOTONS EMERGING FROM THE SUN AFTER ~10K YEARS

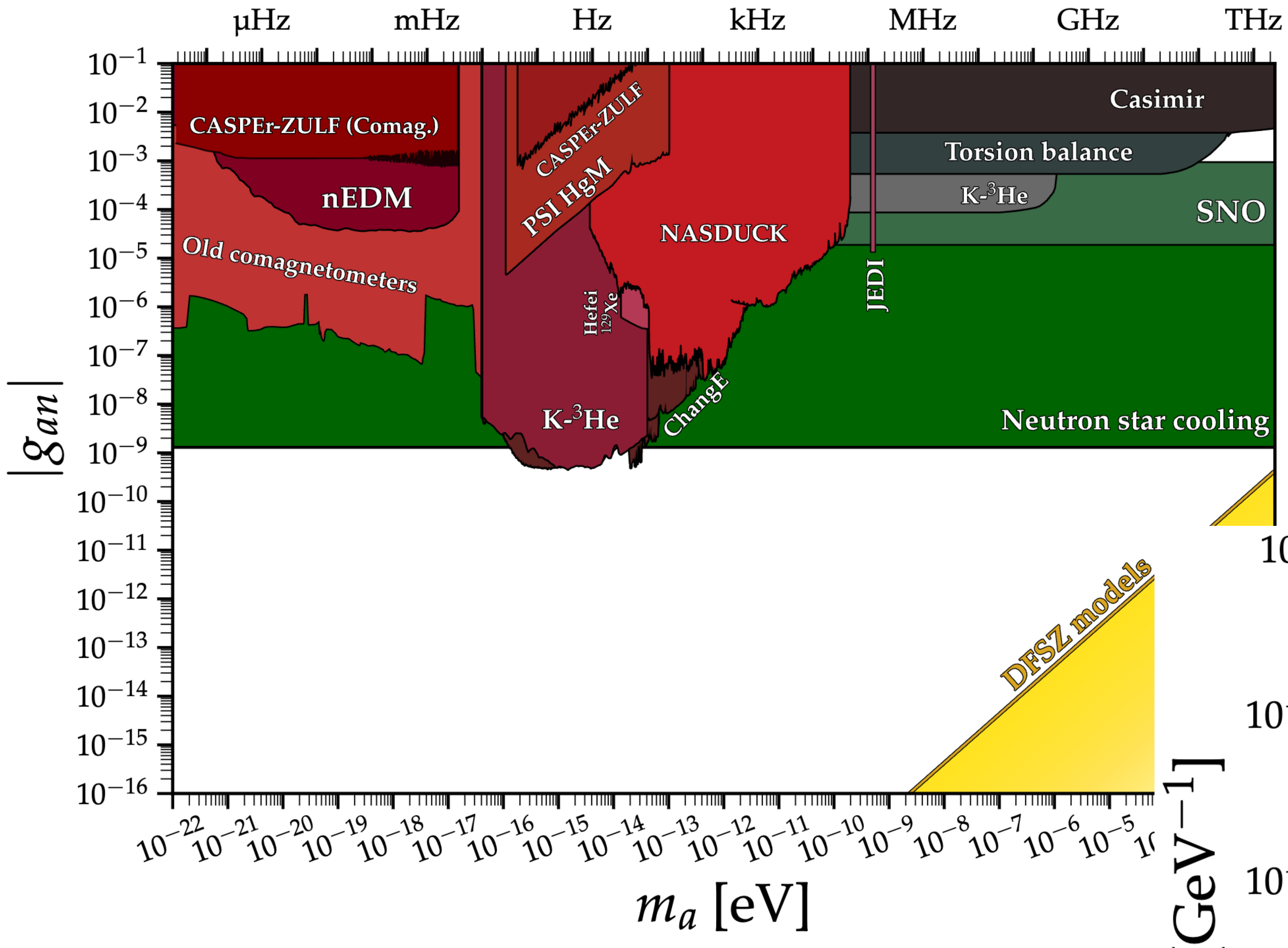


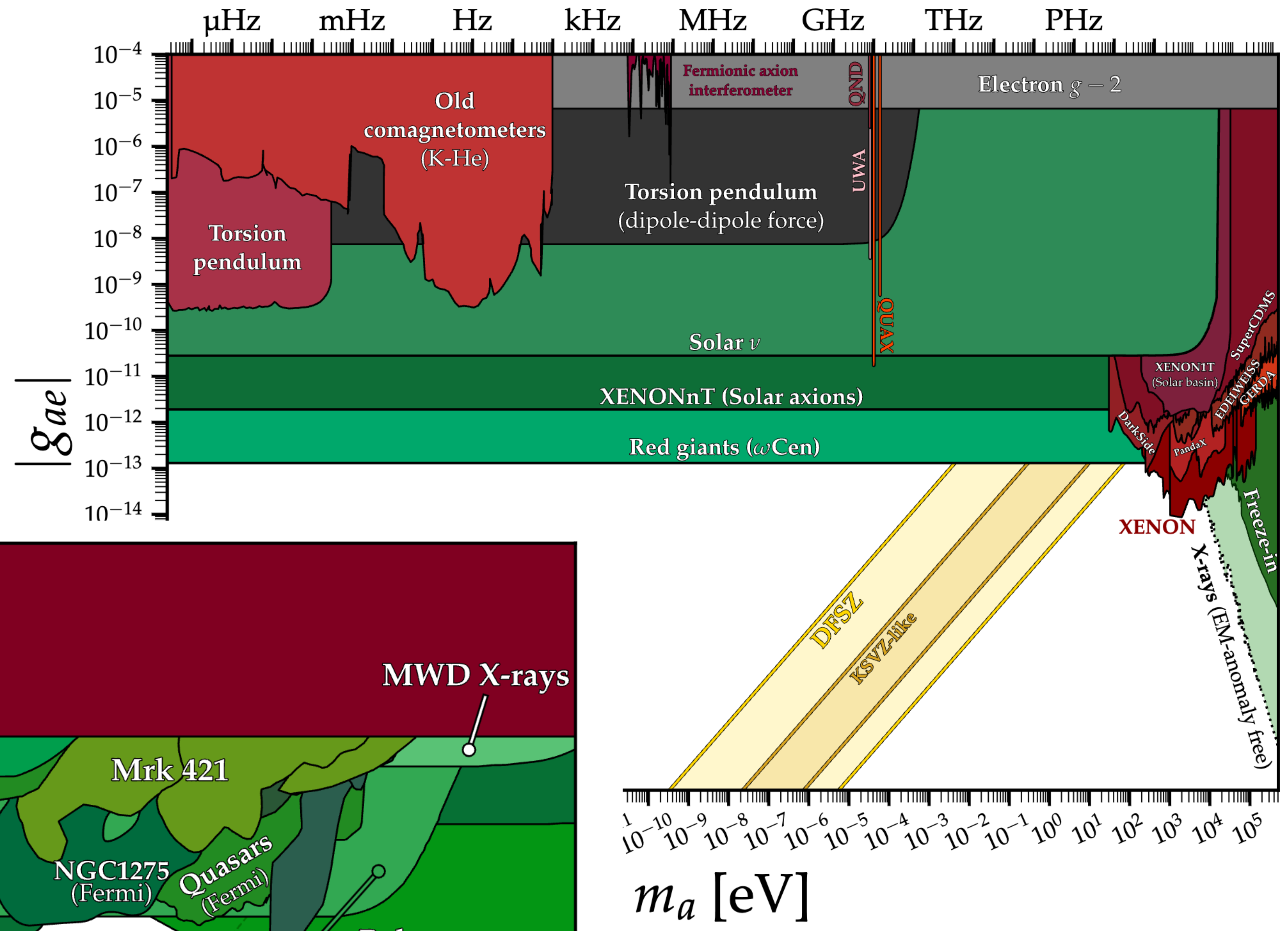
“Free streaming”
photons travel to us without running into much matter

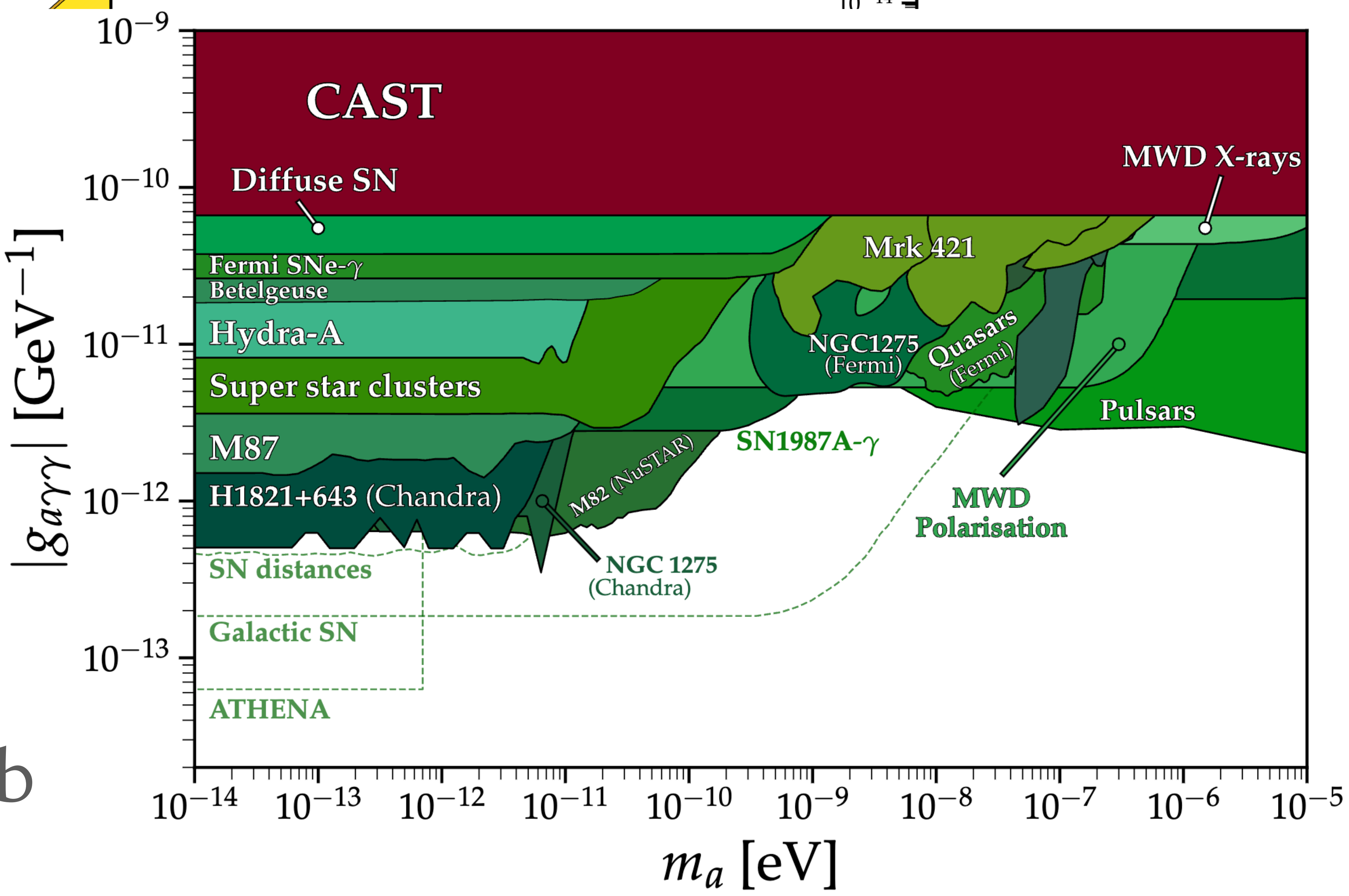
“Photosphere”
the “surface” of the sun -- where the photons we see emerge from the sun and start to “free stream”

“Random Walk”
in the interior of the sun, photons are constantly absorbed and scattered by matter

STELLAR CONSTRAINTS ON AXIONS

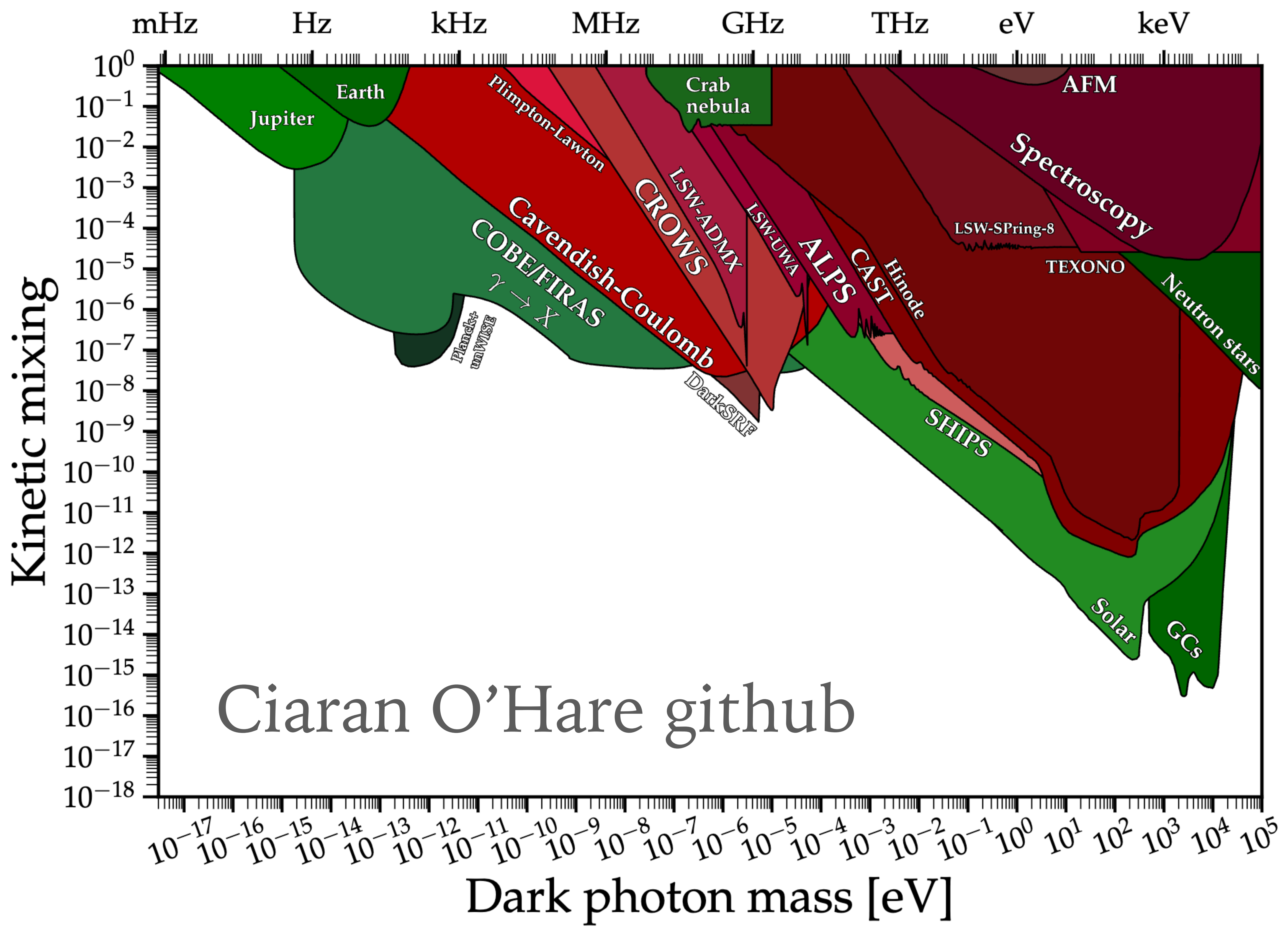


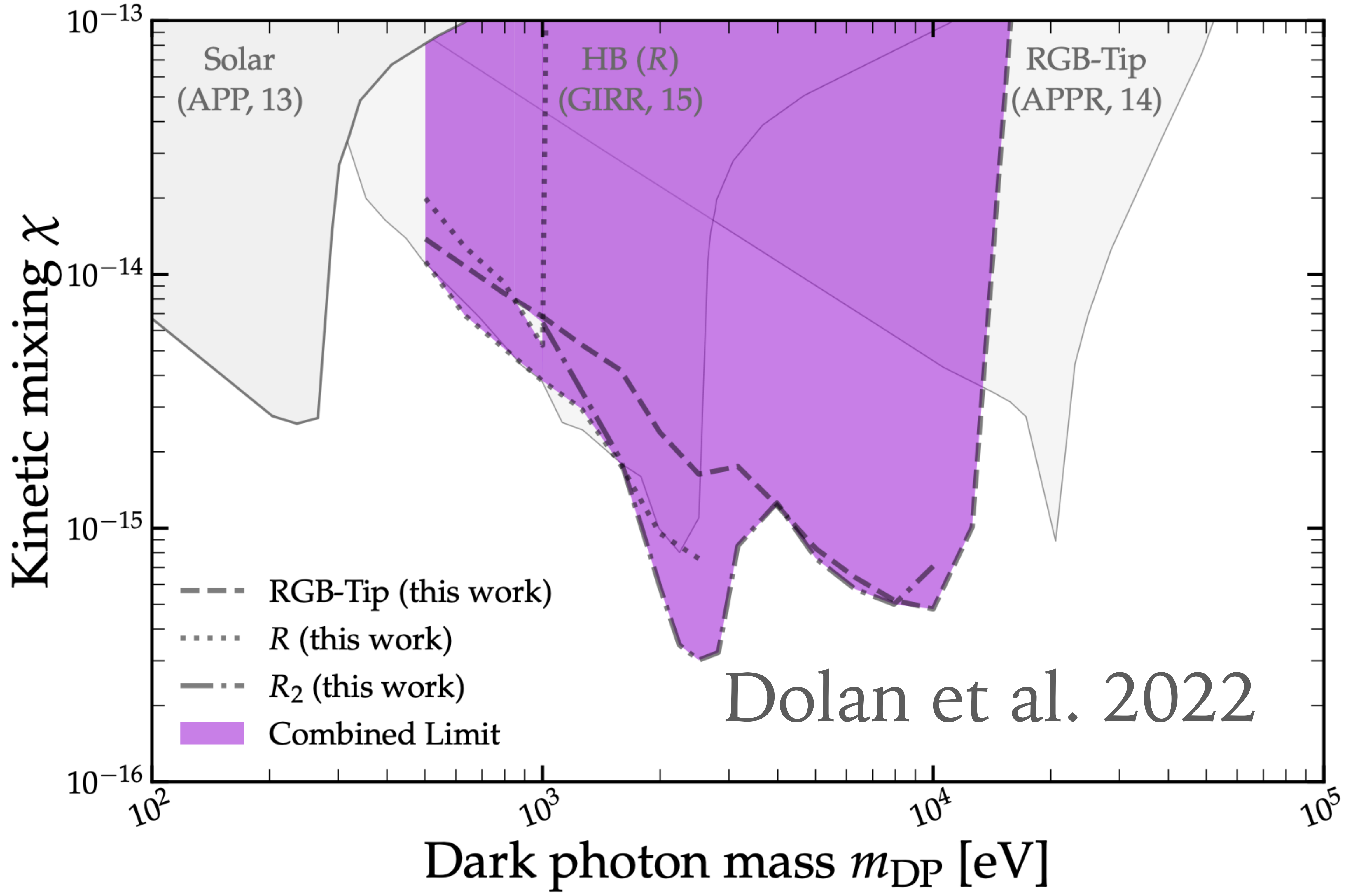




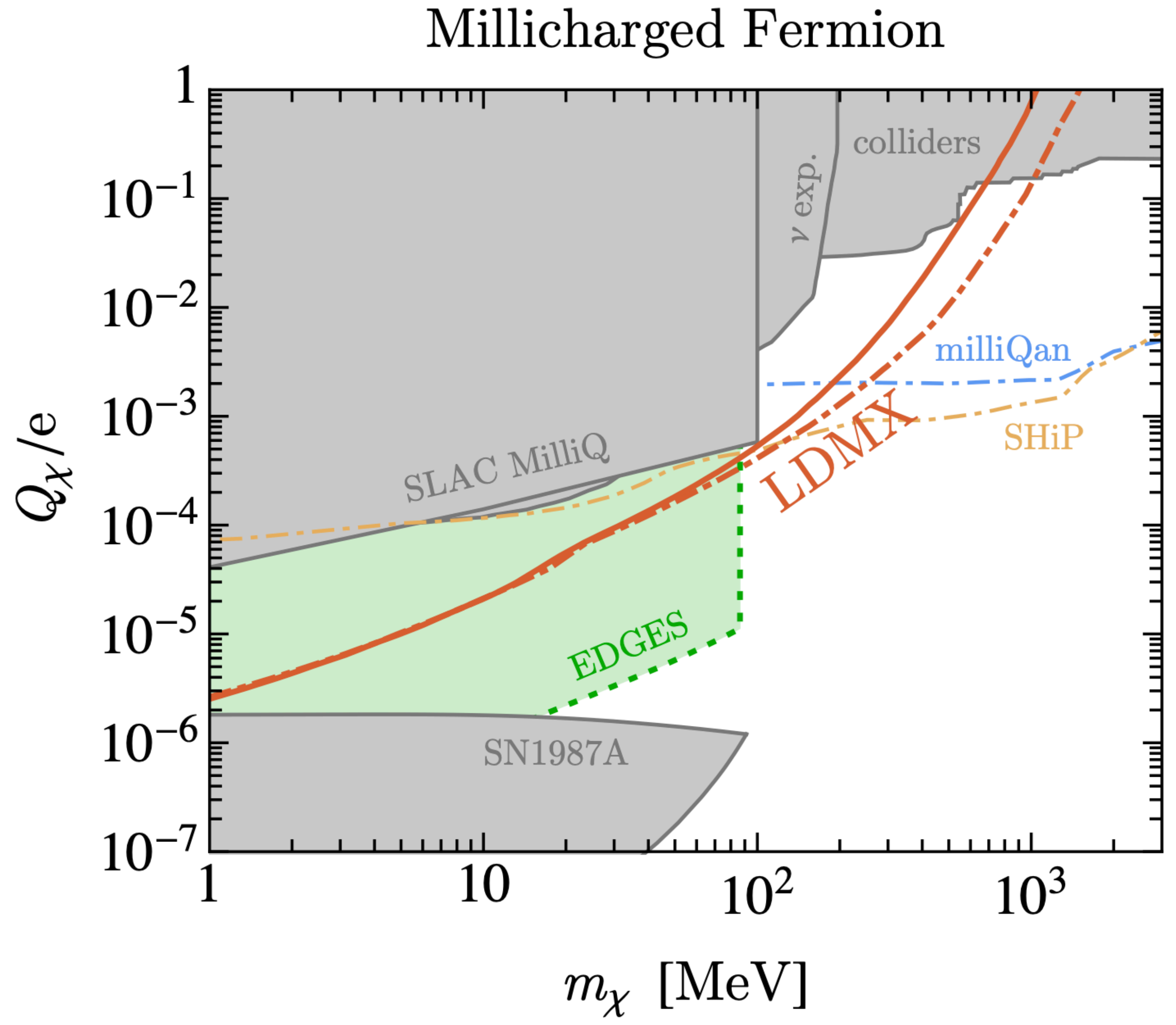
All from Ciaran O'Hare's github

STELLAR CONSTRAINTS ON DARK PHOTONS

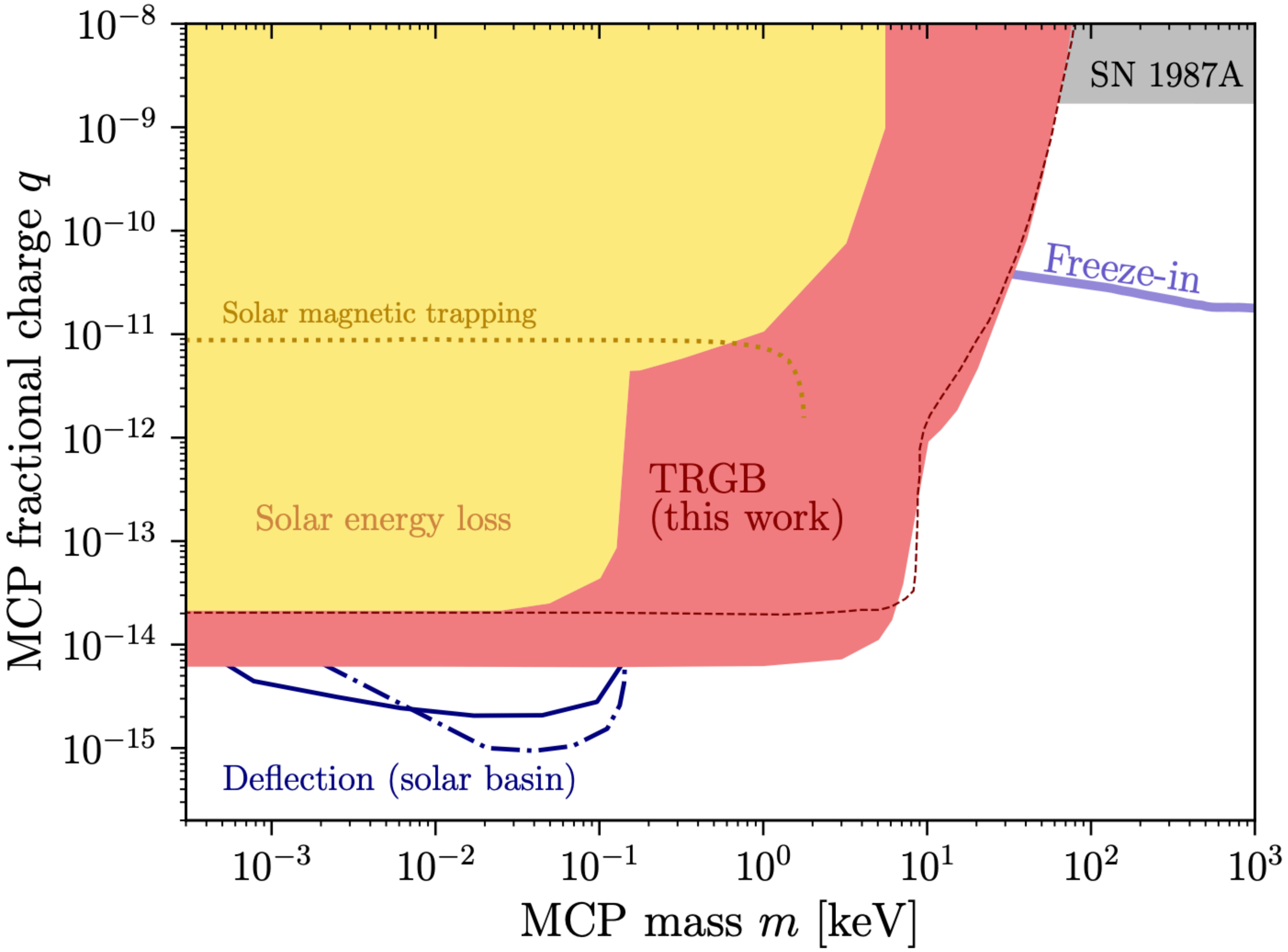




STELLAR CONSTRAINTS ON MILLICHARGE

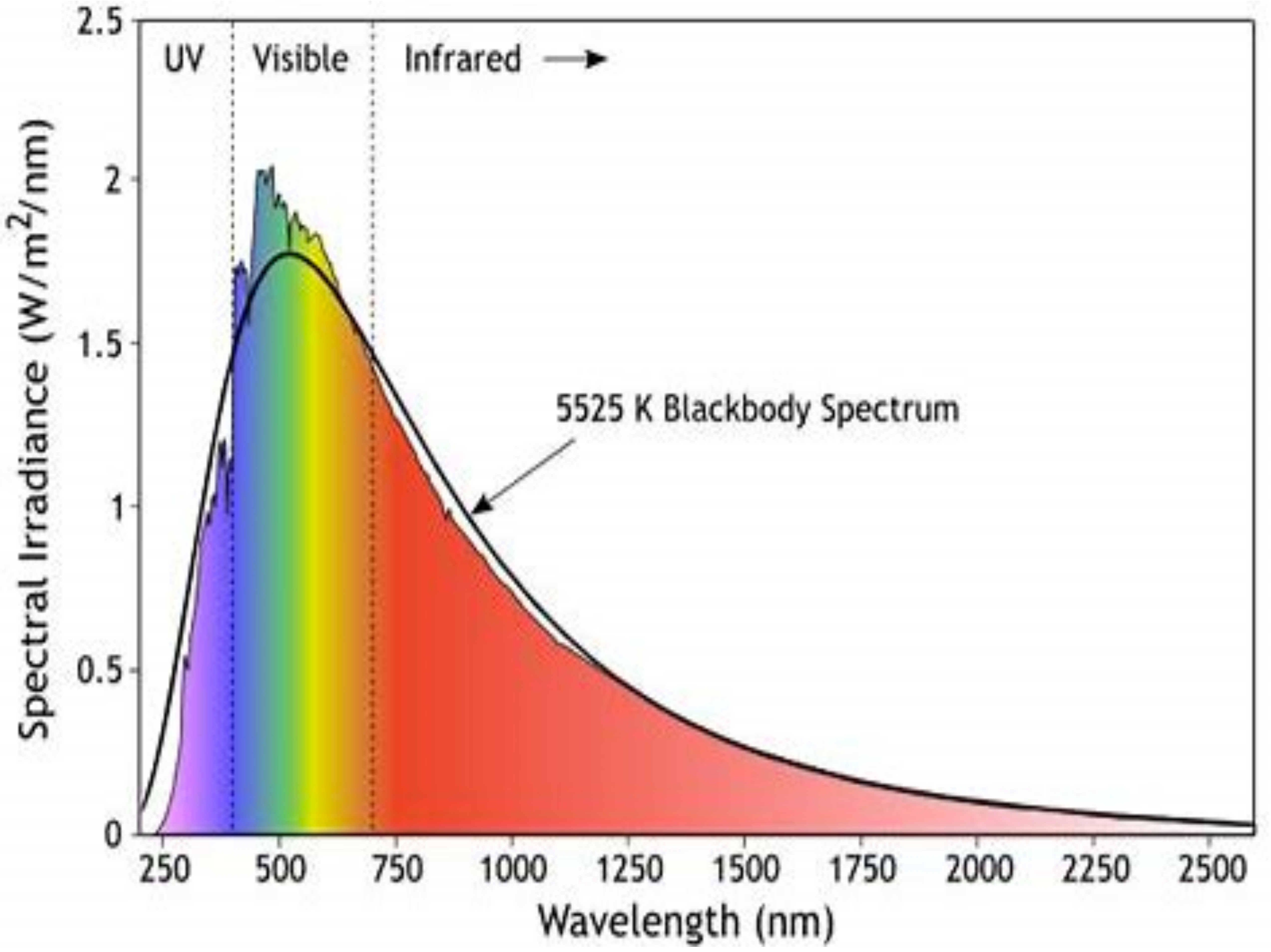


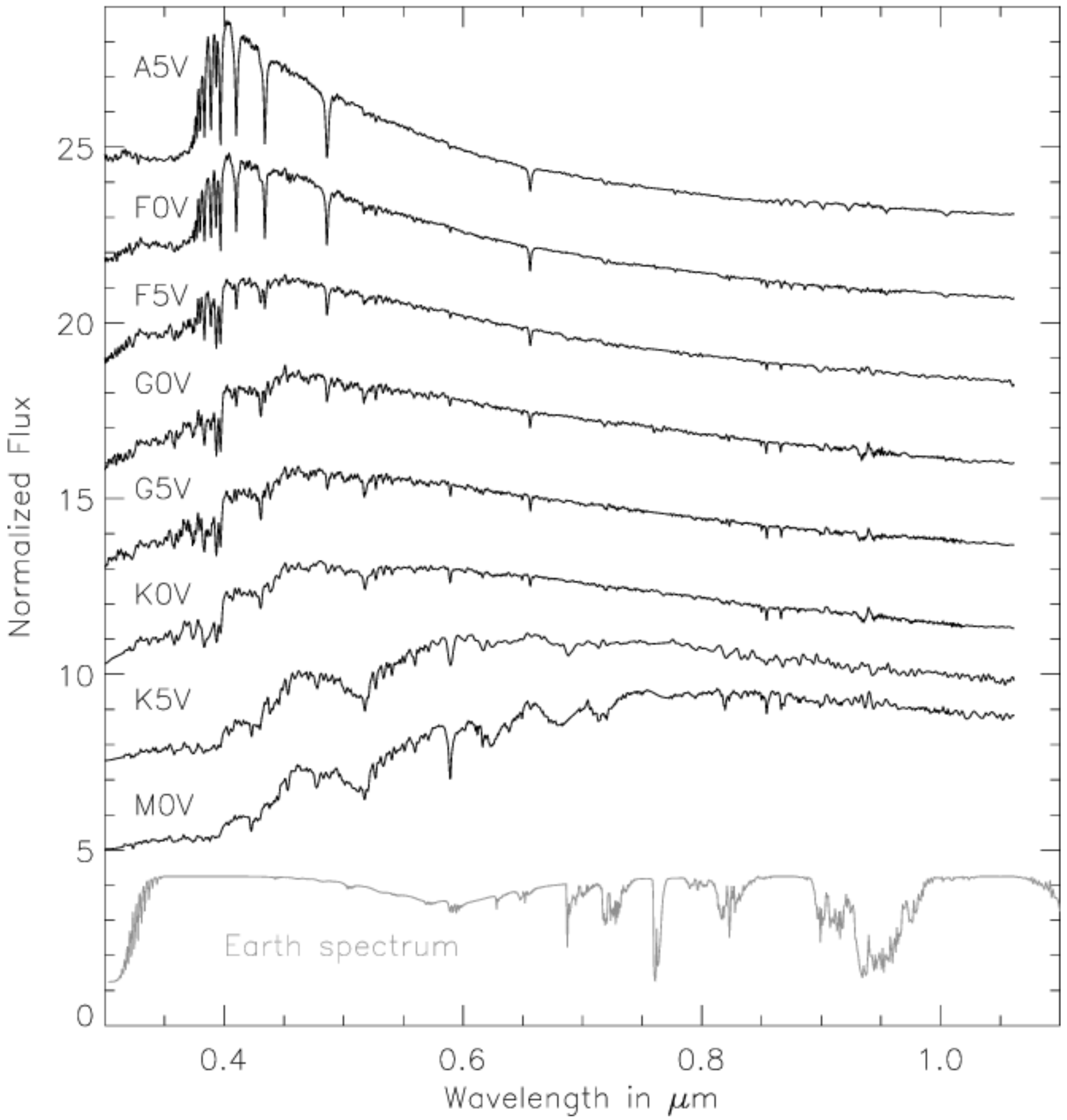
contrast with terrestrial searches e.g. Berlin et al. (2019)



Fung, Heeba, Liu, Muralidharan, **KS**, Vincent (2024)

STELLAR SPECTRA

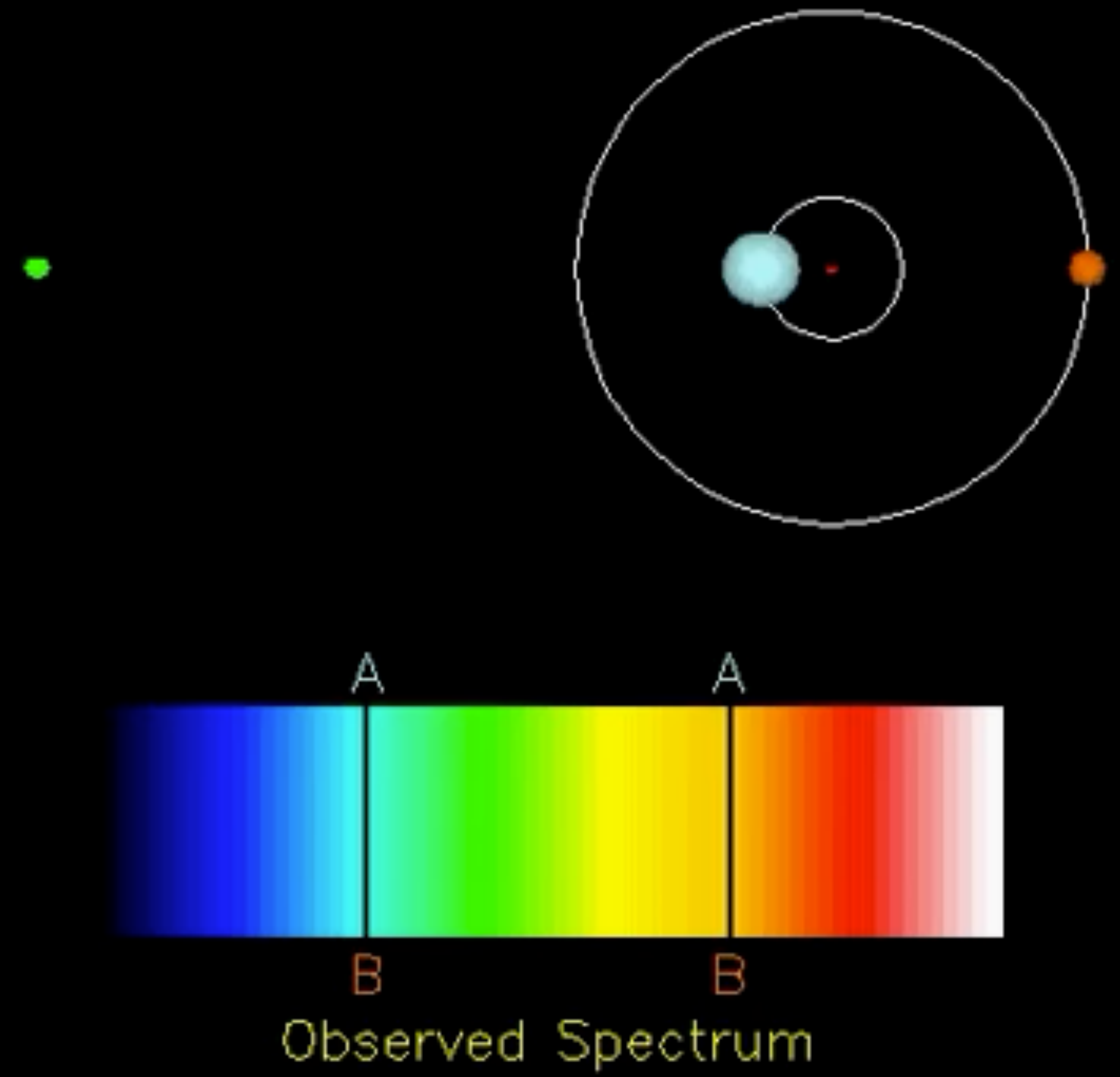




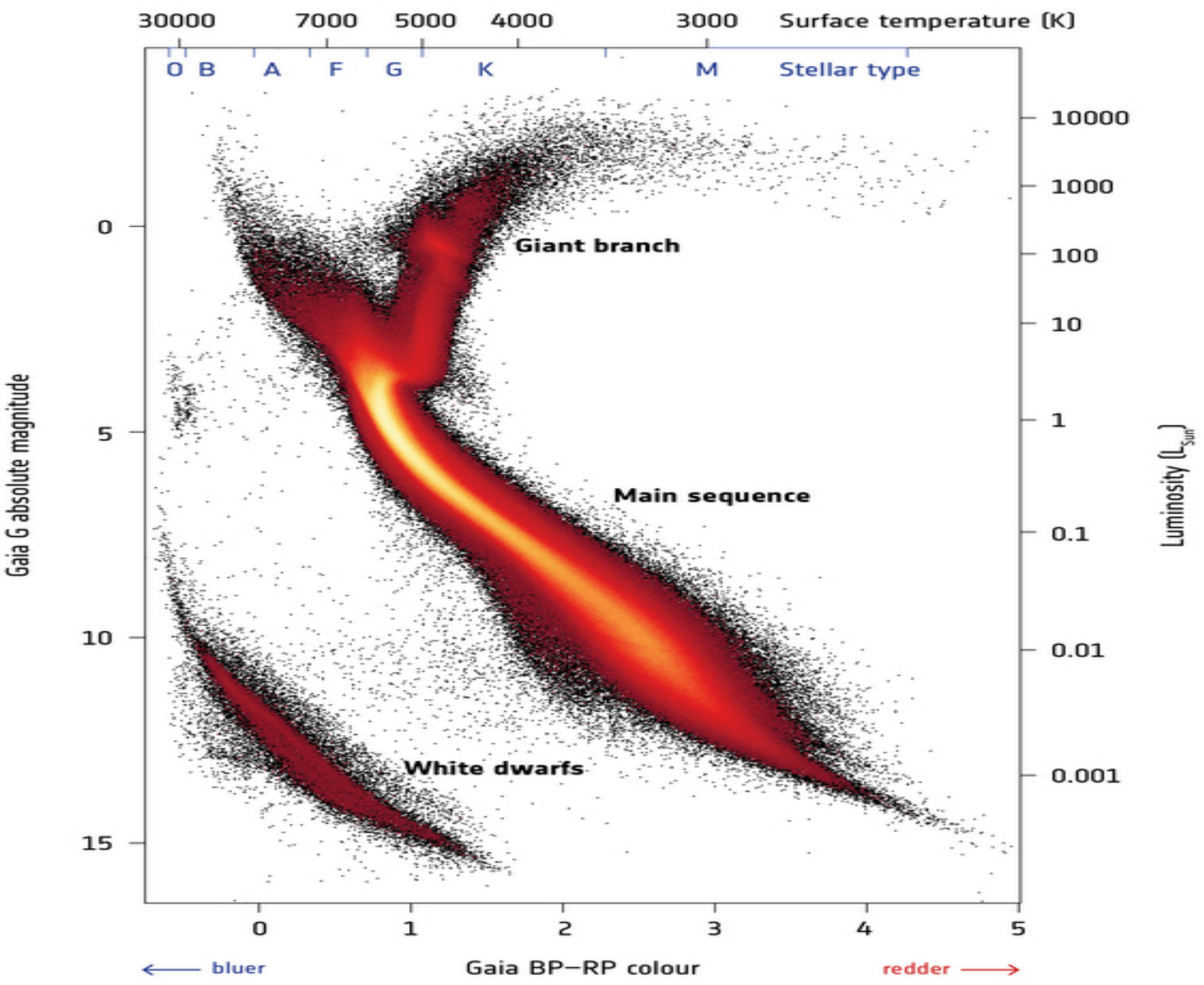
ECLIPSING BINARIES

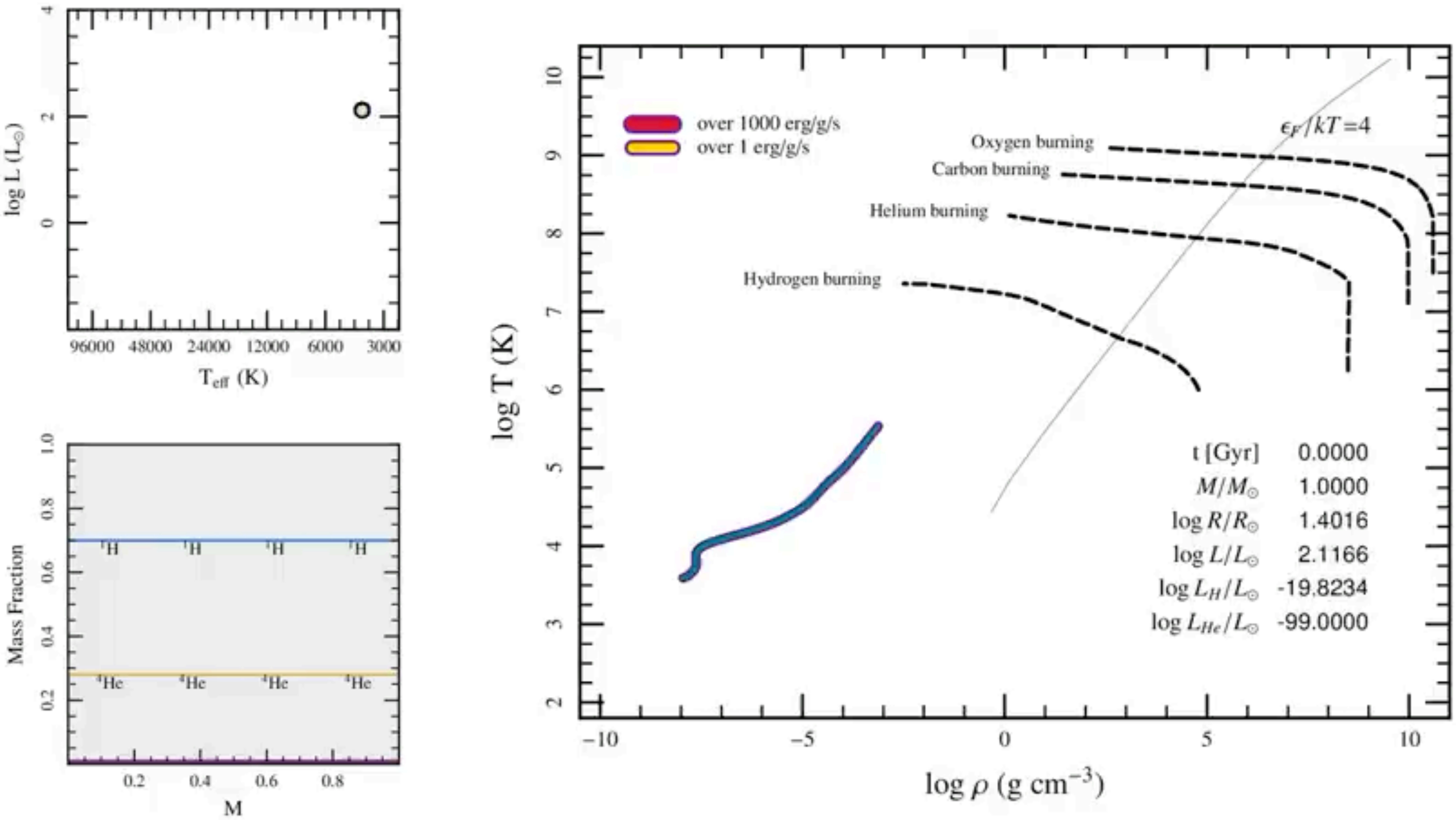
www.eso.org

SPECTROSCOPIC BINARY

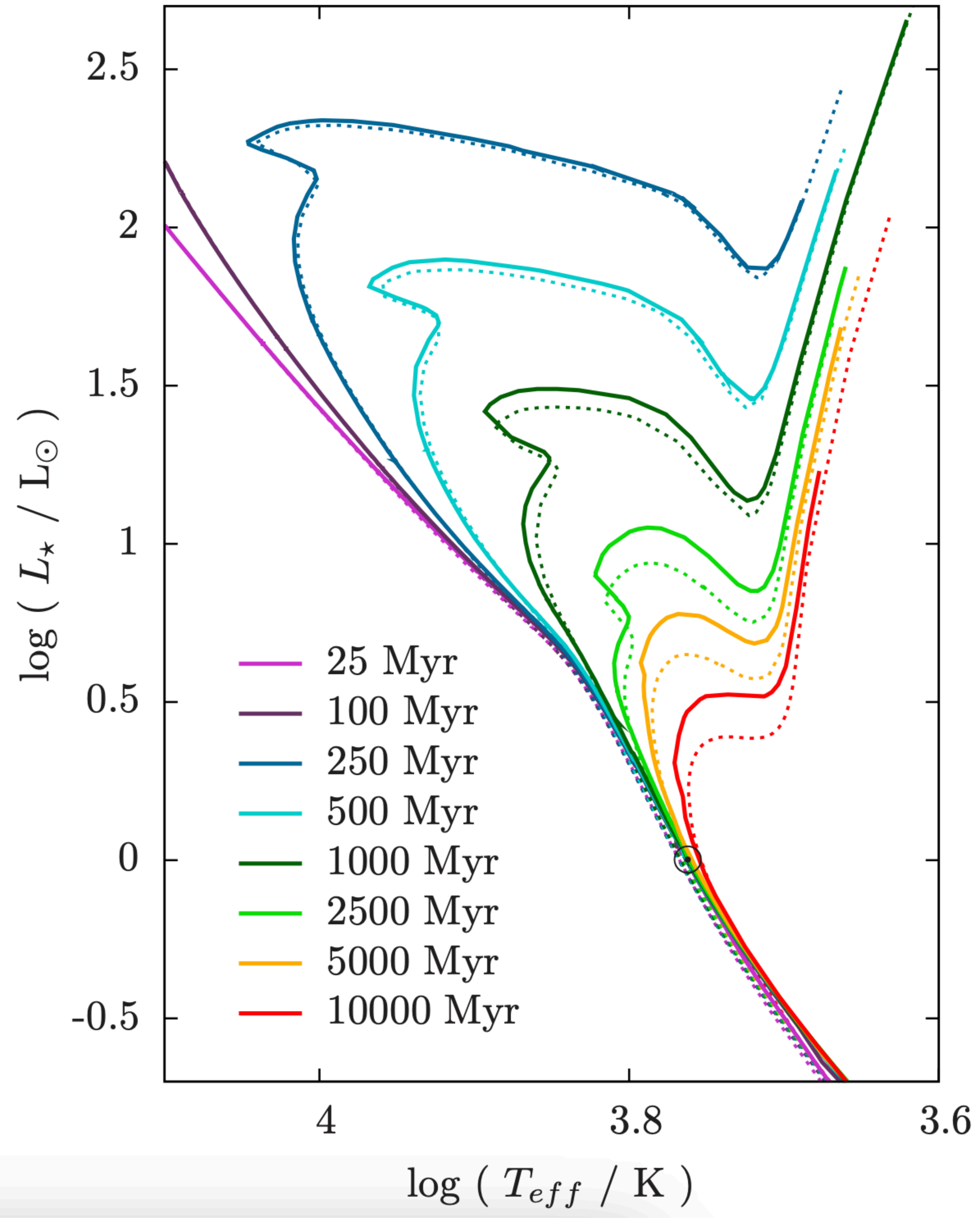


HERTZSPRUNG–RUSSELL DIAGRAM

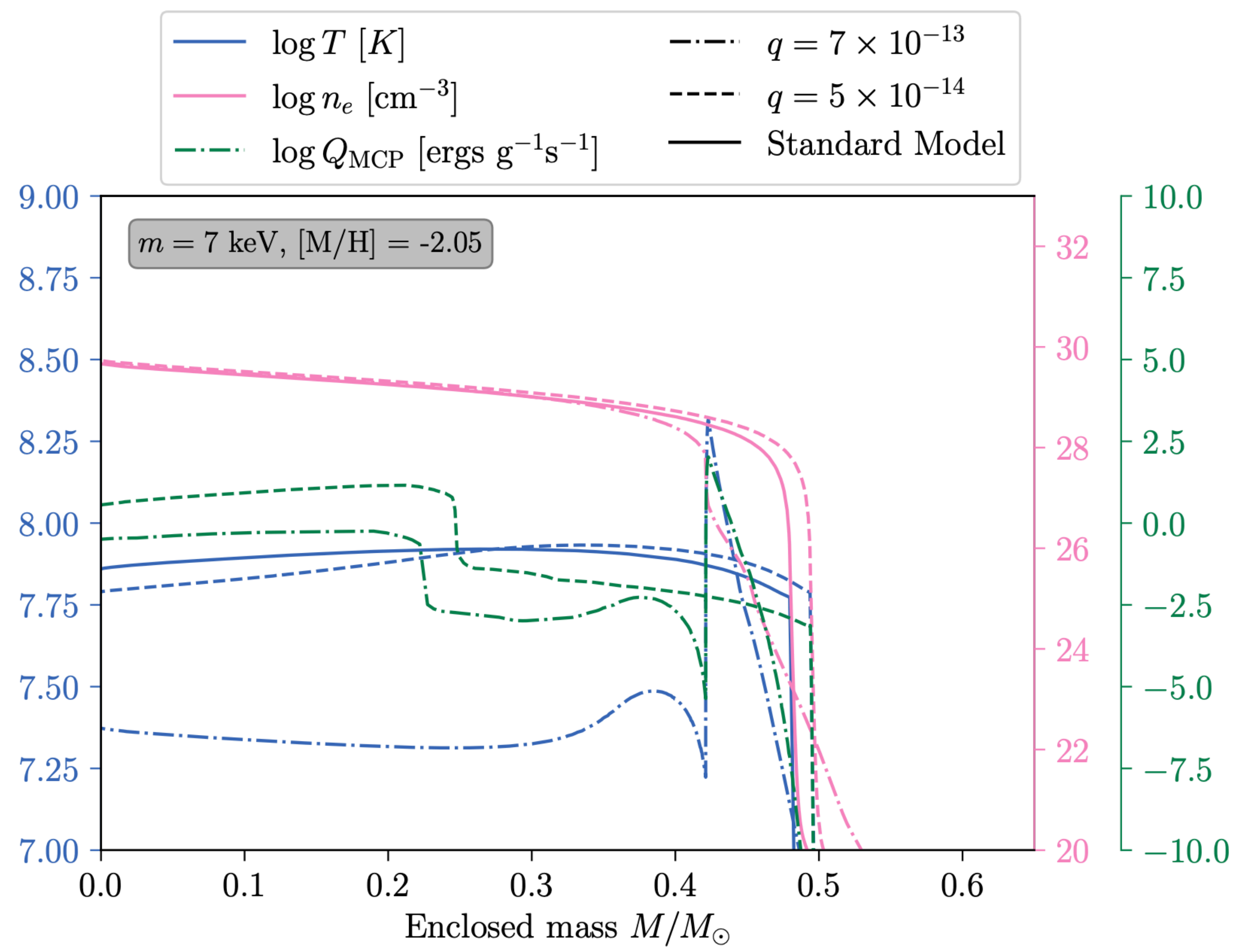


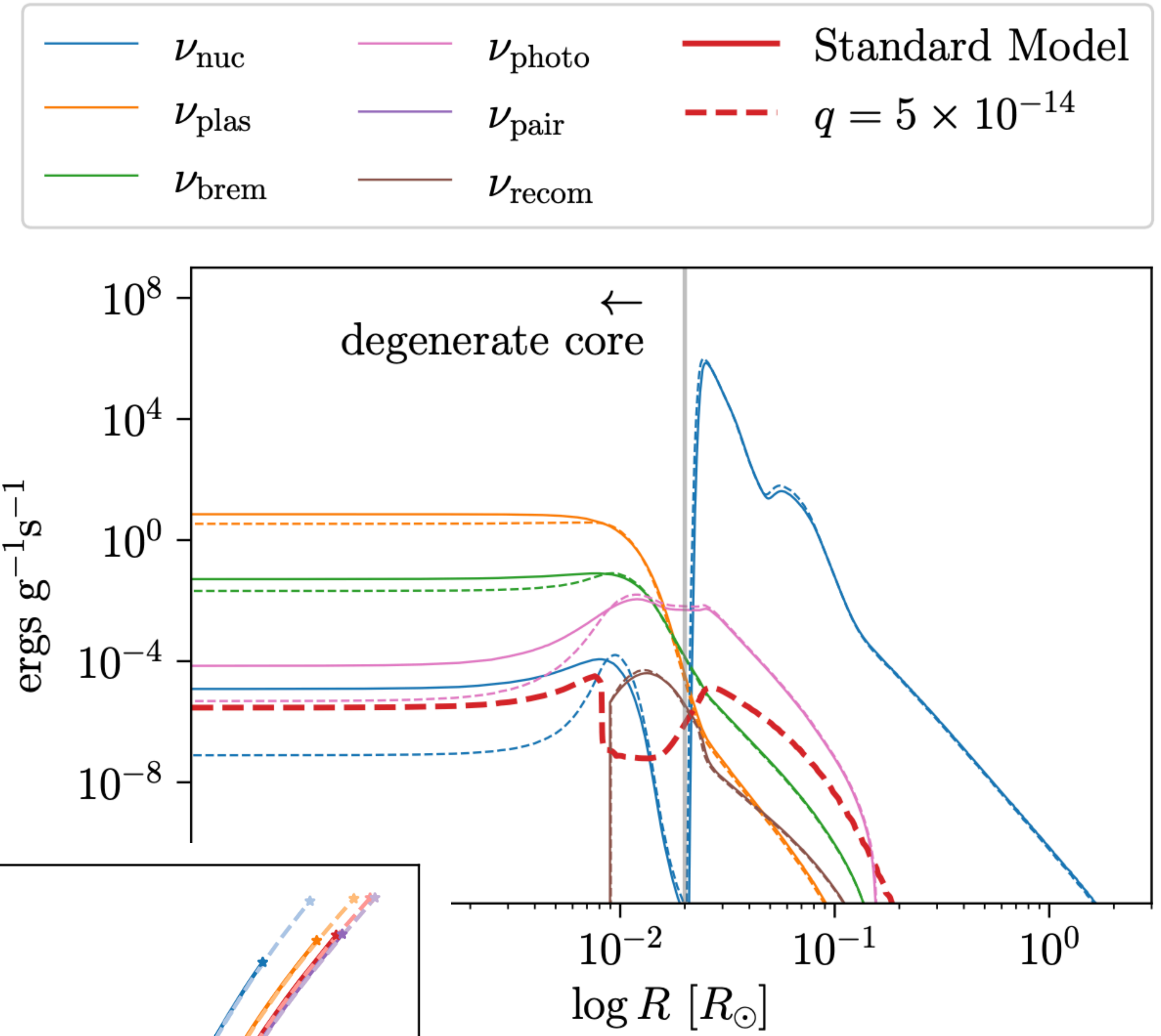

log L (L$_\odot$)
T_{eff} (K)
96000 48000 24000 12000 6000 3000
Mass Fraction
M
^{1}H
^{4}He
over 1000 erg/g/s
over 1 erg/g/s
Oxygen burning
Carbon burning
Helium burning
Hydrogen burning
$\epsilon_F/kT=4$
t [Gyr] 0.0000
$M/M_\odot$ 1.0000
$\log R/R_\odot$ 1.4016
$\log L/L_\odot$ 2.1166
$\log L_H/L_\odot$ -19.8234
$\log L_{He}/L_\odot$ -99.0000
log T (K)
log ρ (g cm^{-3})

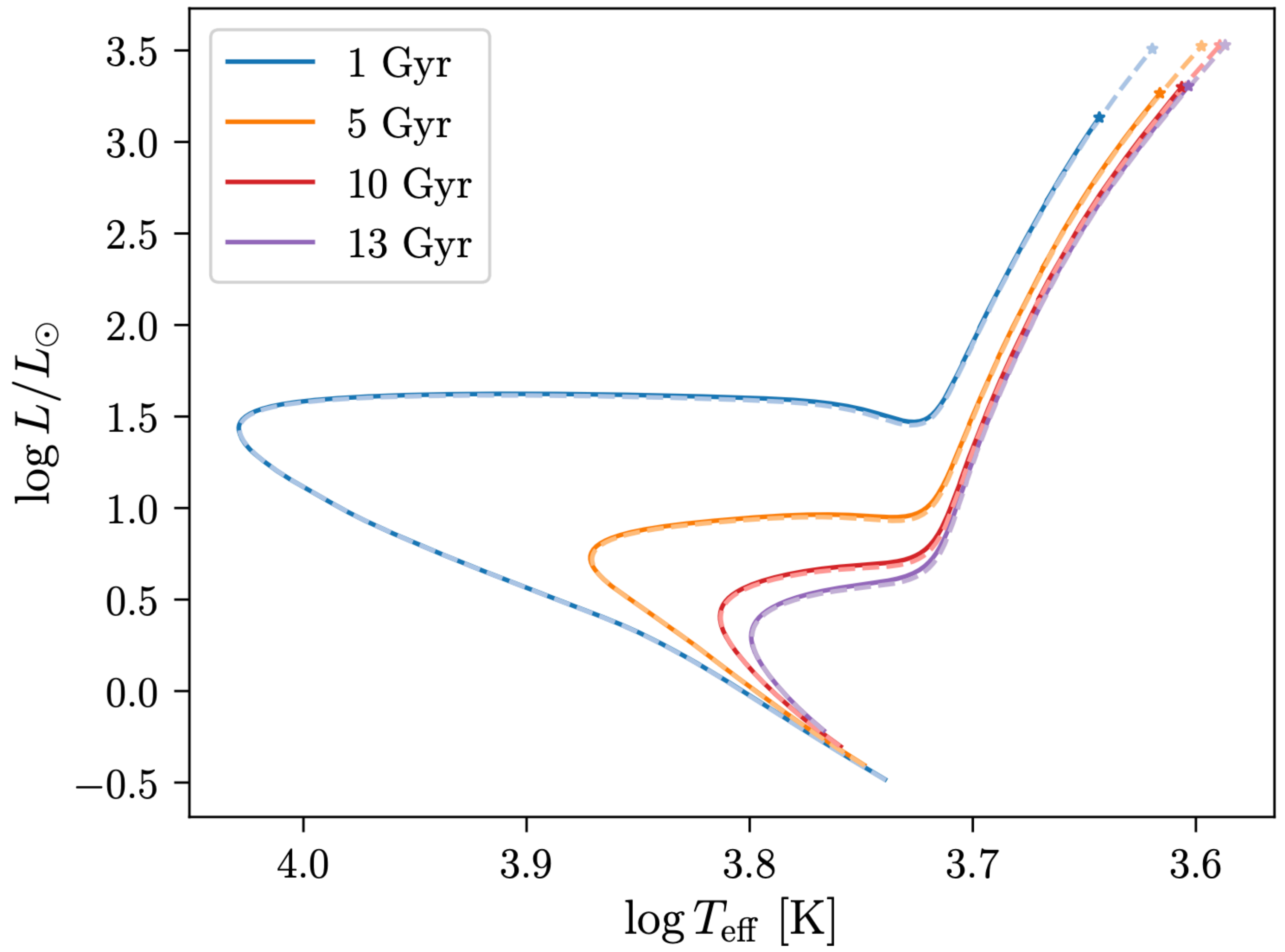
BSM EFFECTS ON POST-MAIN SEQUENCE



WIMPs annihilating in stars between 0.7-3.5 solar masses (Casanellas & Lopes)

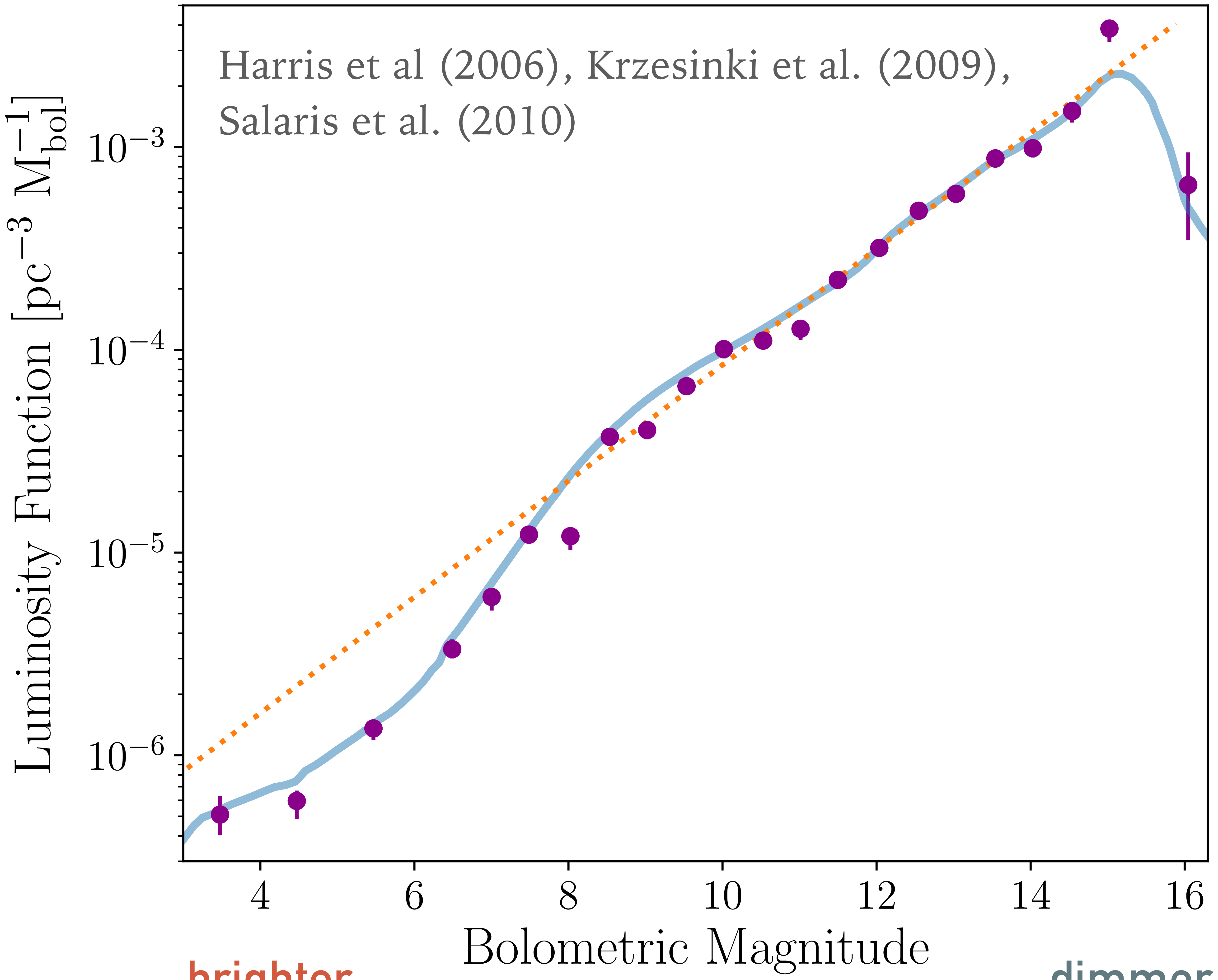






Millicharged particle emission (Fung, Heeba, Liu, Muralidharan, **KS**, Vincent, 2024)

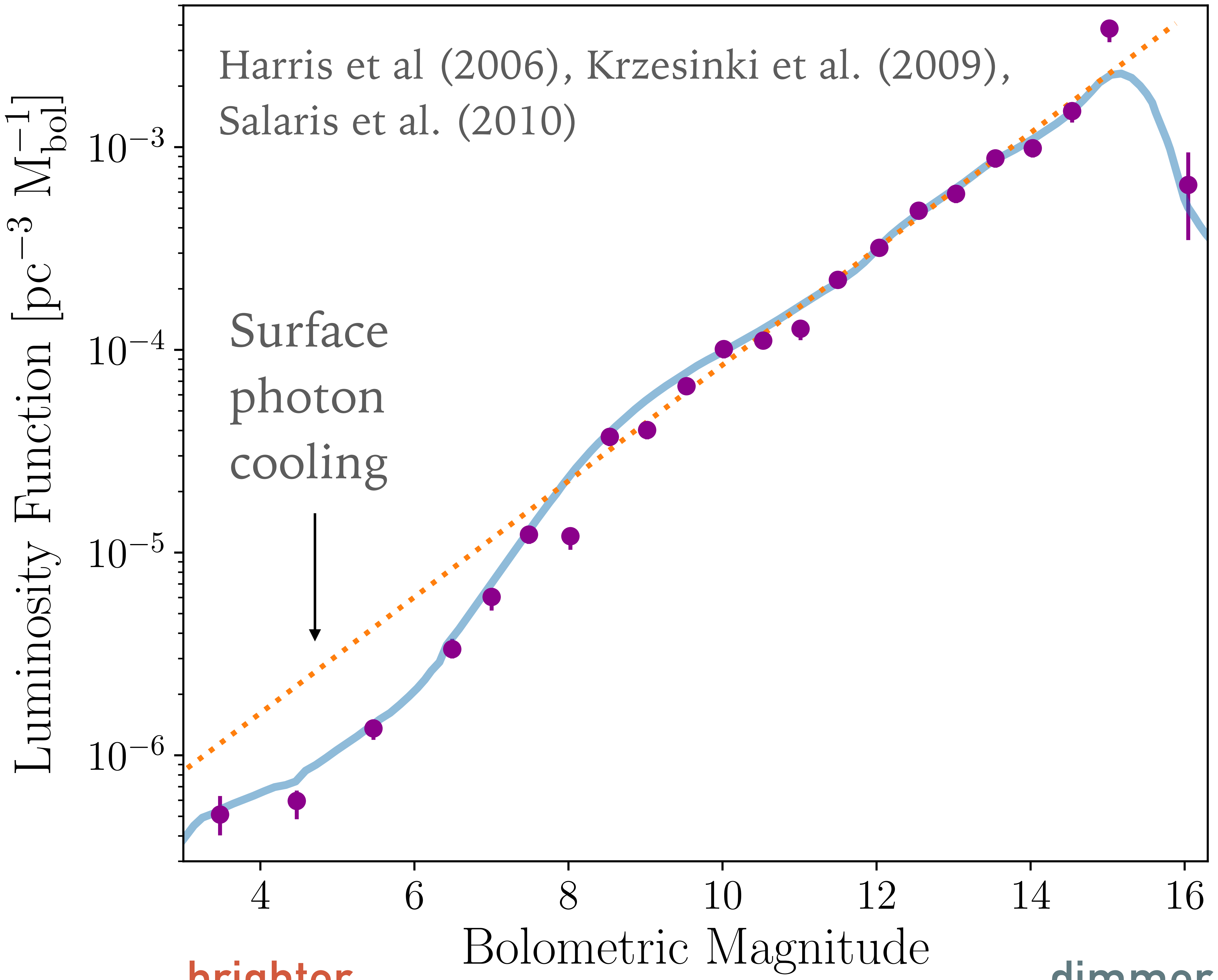
WHITE DWARF COOLING AND POPULATION



brighter
hotter

dimmer
cooler

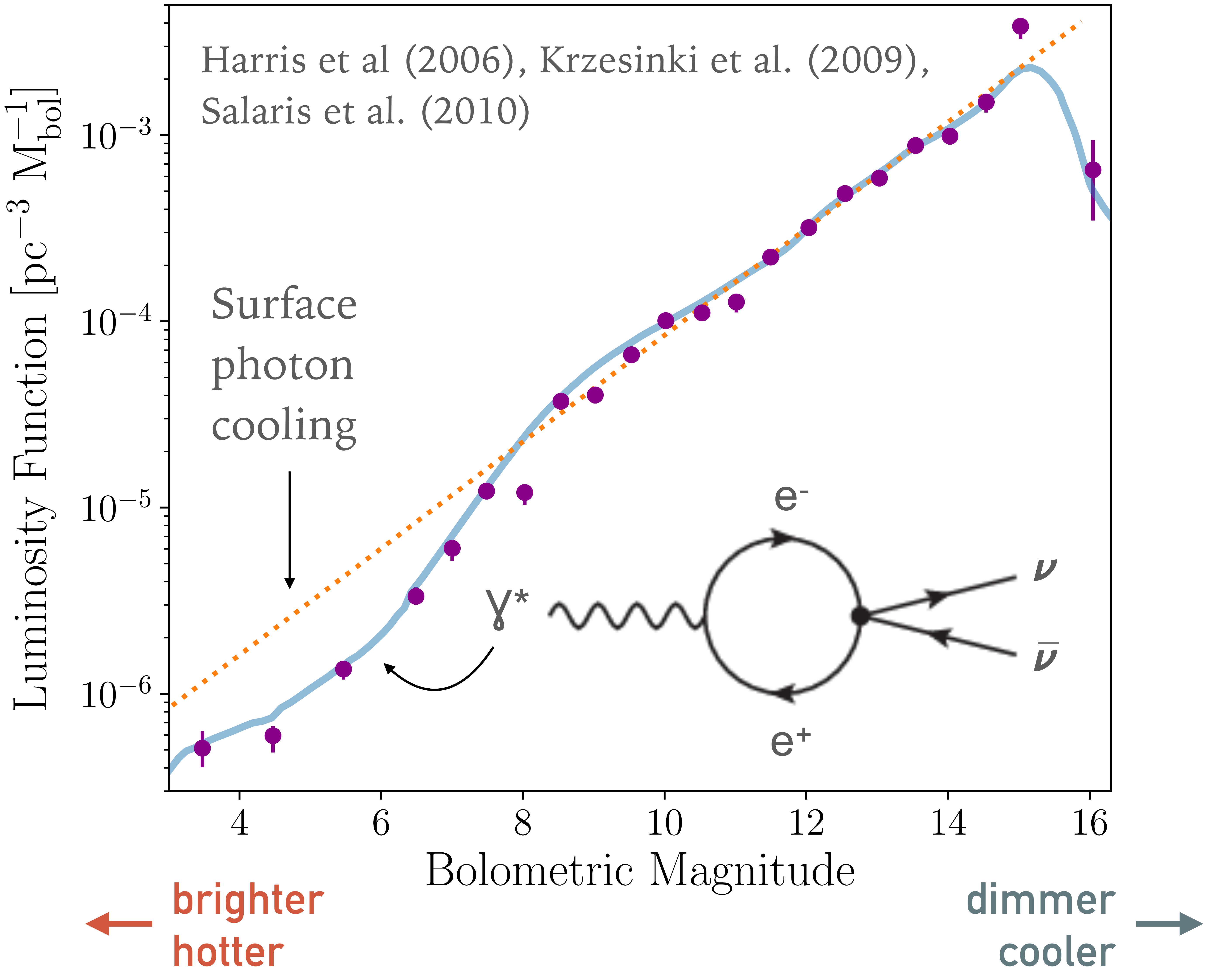
WHITE DWARF COOLING AND POPULATION



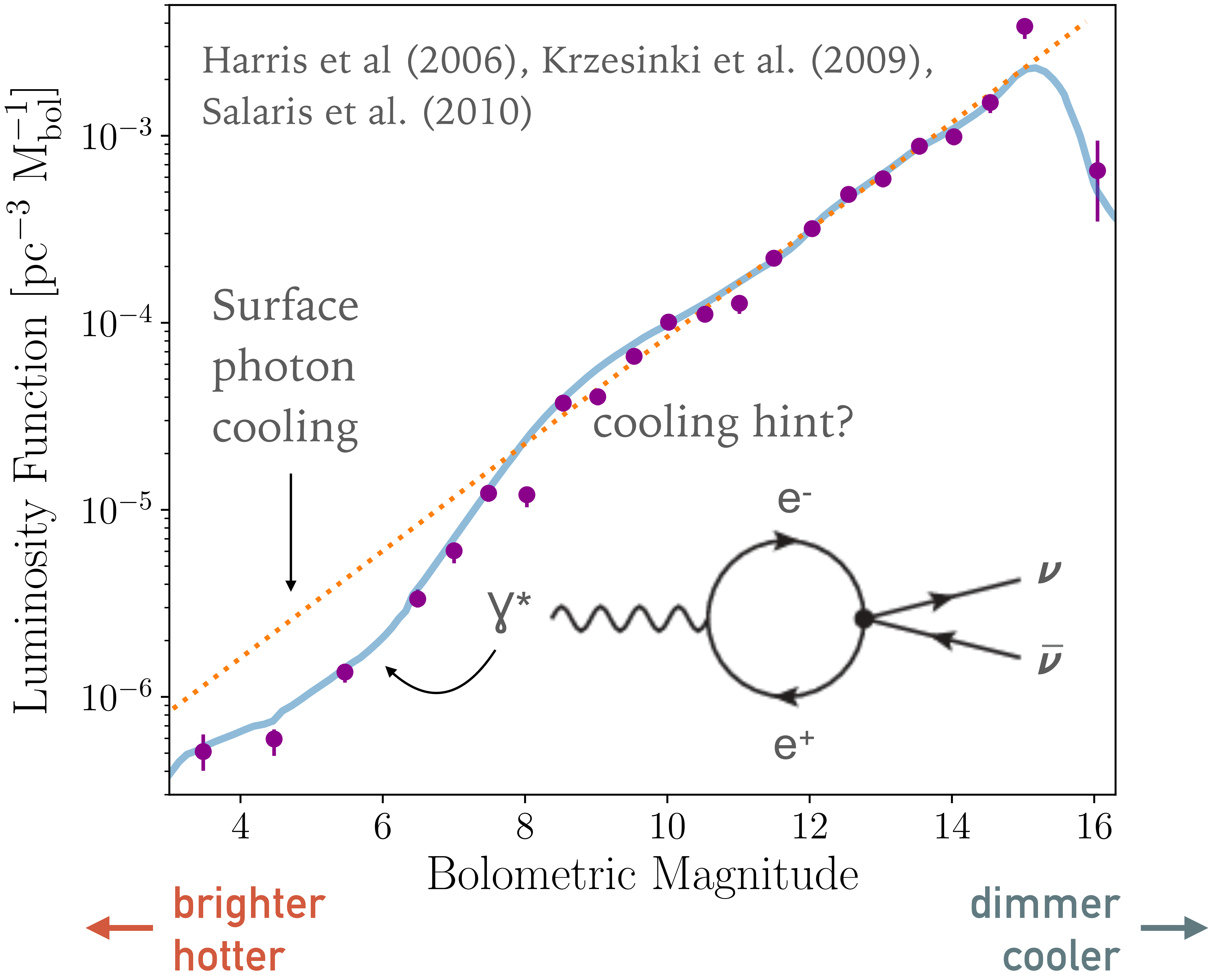
brighter
hotter

dimmer
cooler

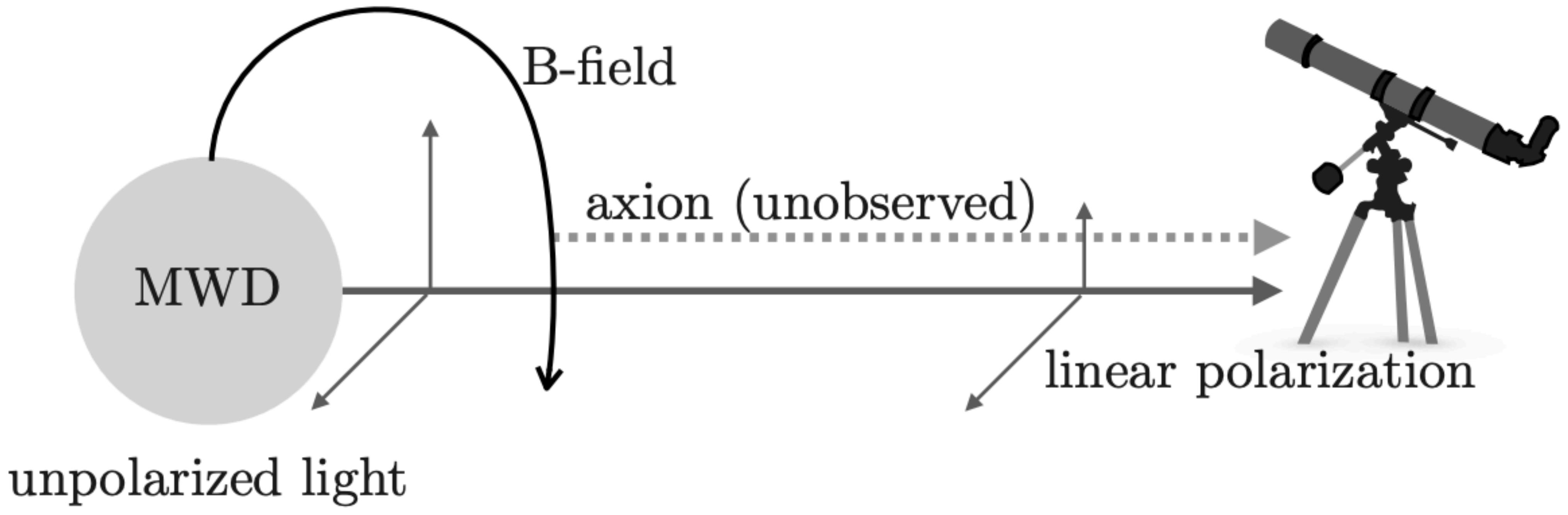
WHITE DWARF COOLING AND POPULATION

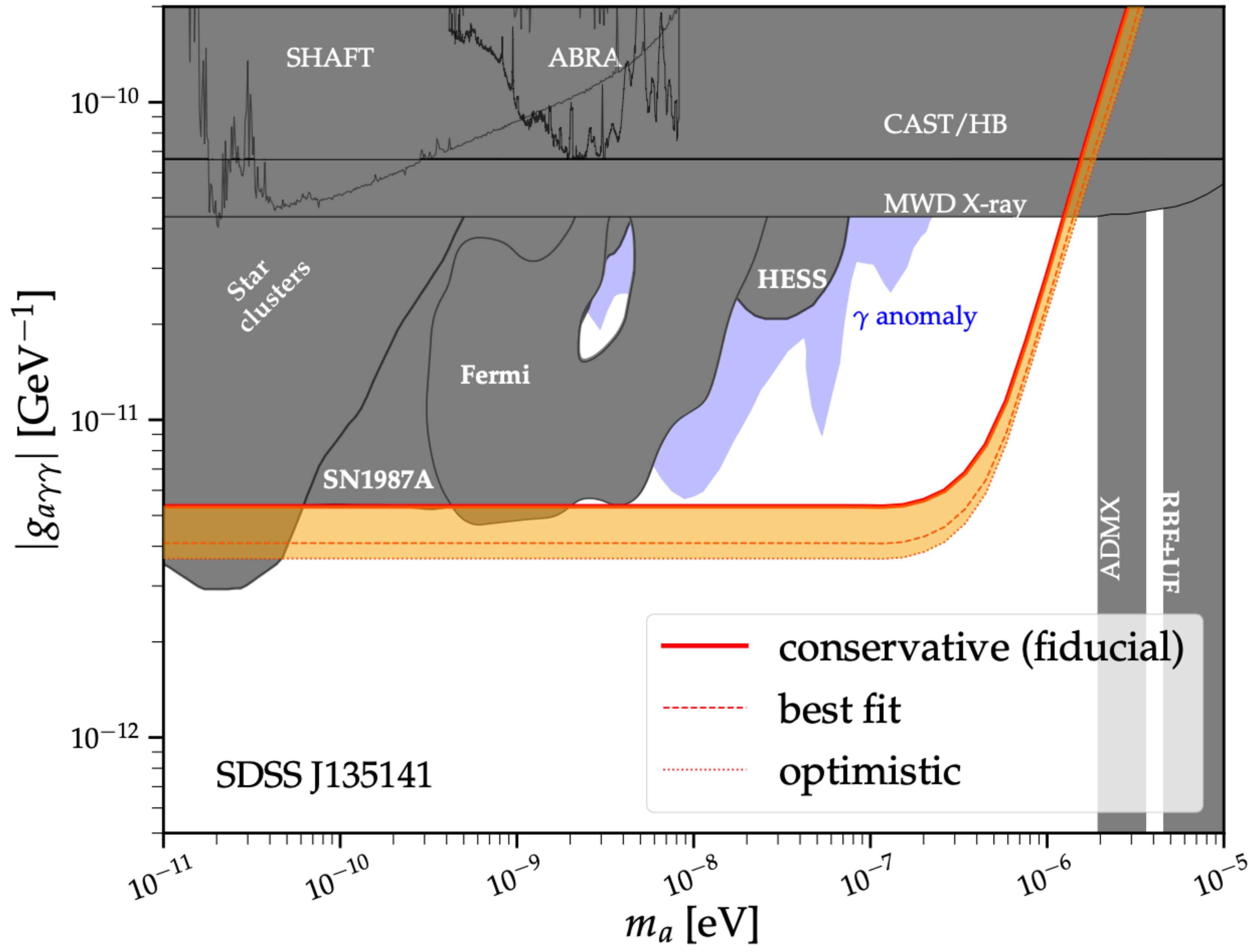


WHITE DWARF COOLING AND POPULATION

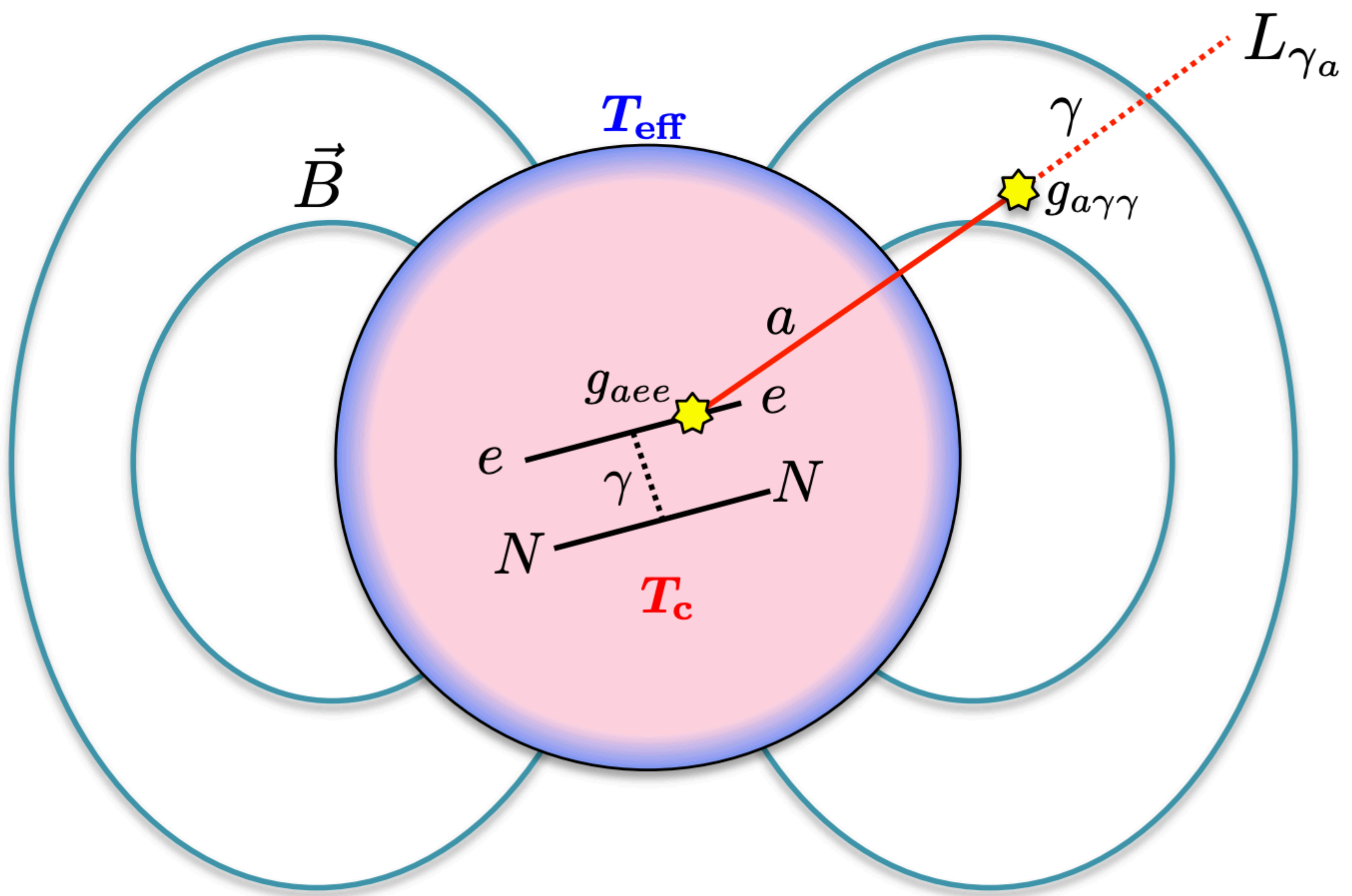


OTHER WHITE DWARF CONSTRAINTS ON BSM

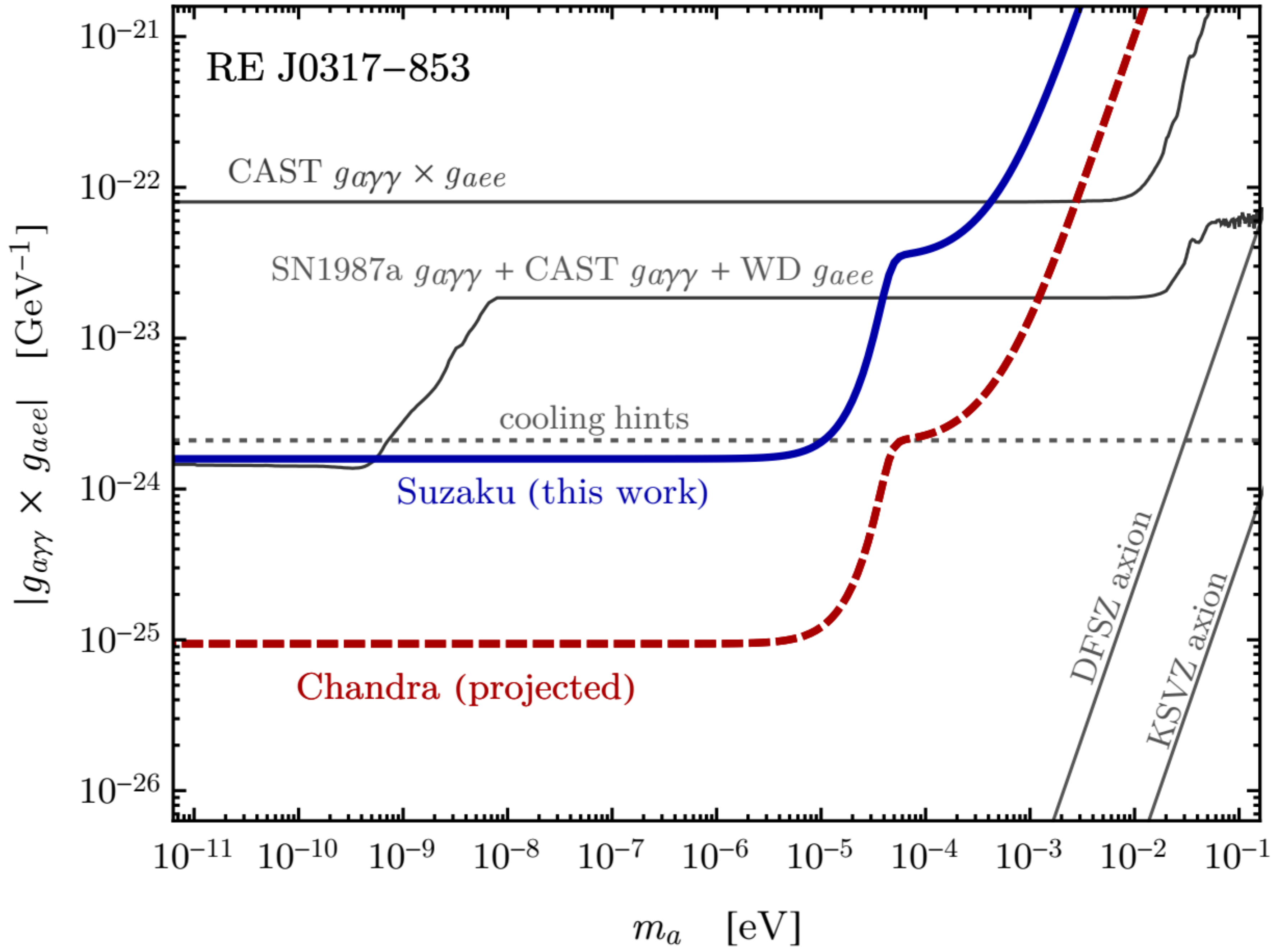




Dessert, Dunsky, Safdi (2022)

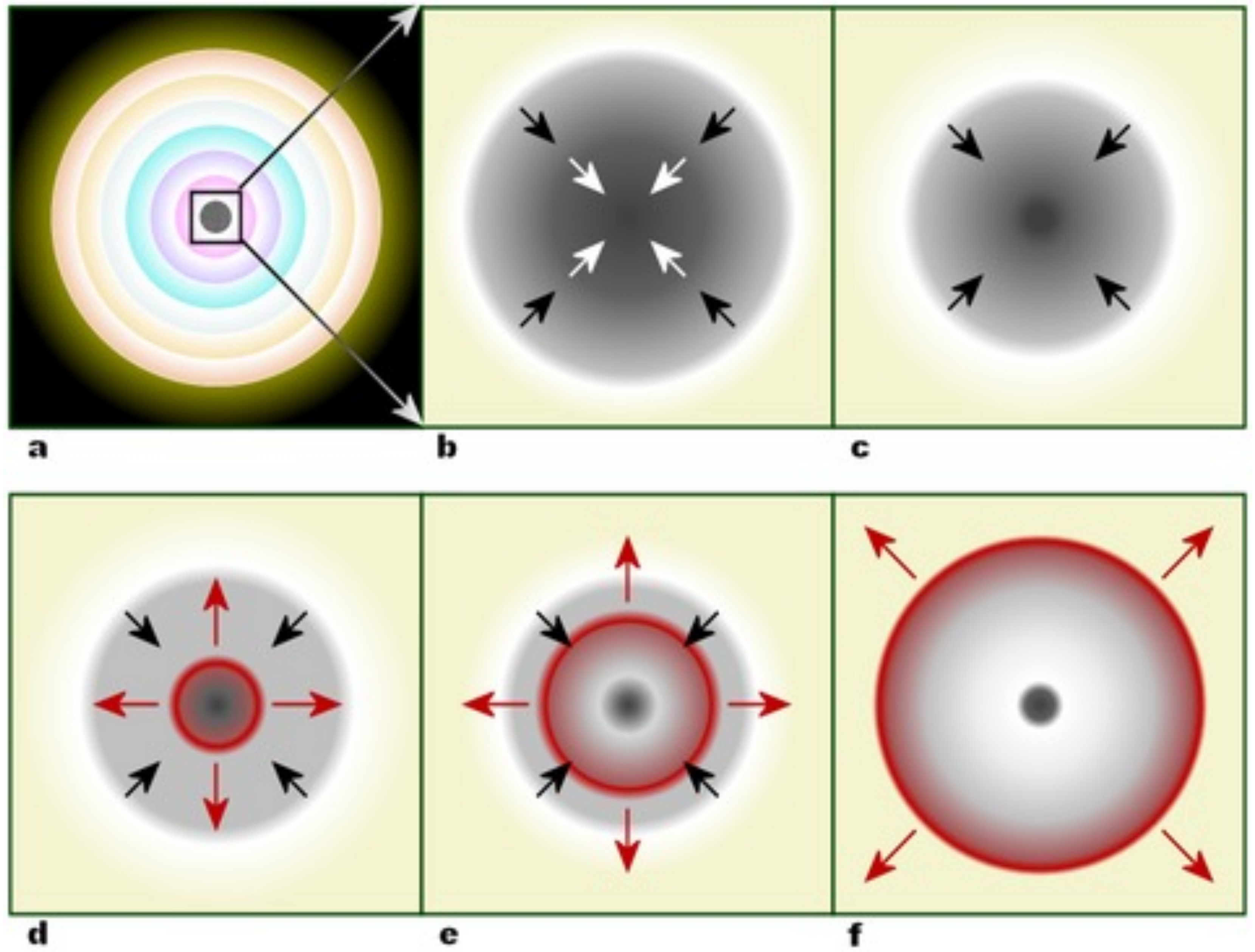


Dessert, Long, Safdi (2021)



CORE-COLLAPSE (TYPE II) SUPERNOVAE

During core collapse, the layers above the core have no support, so they also plummet downward. When the core collapse is halted by neutron degeneracy pressure, these layers strike the core and the kinetic energy of infall is converted to thermal energy increasing the pressure.

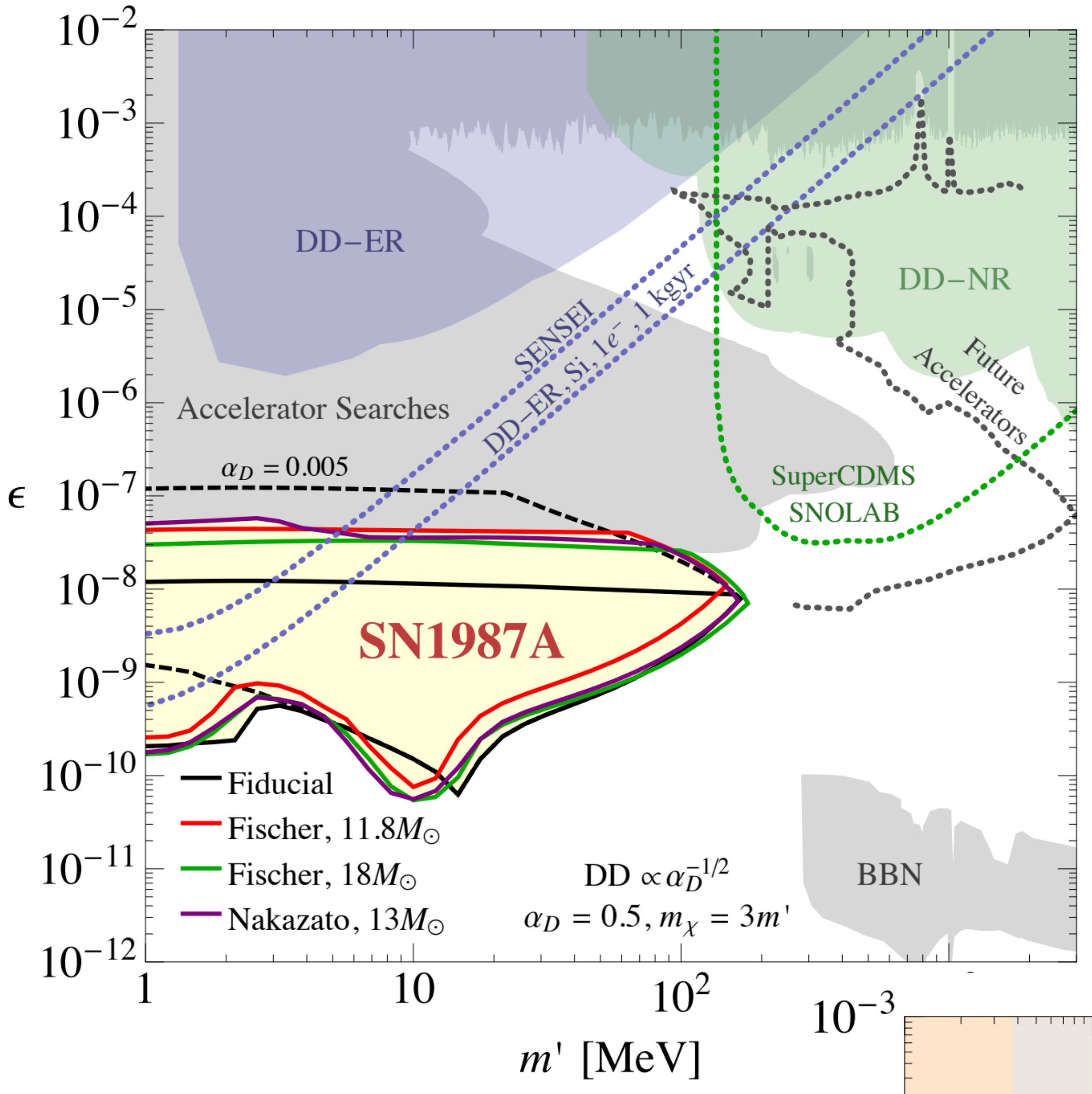


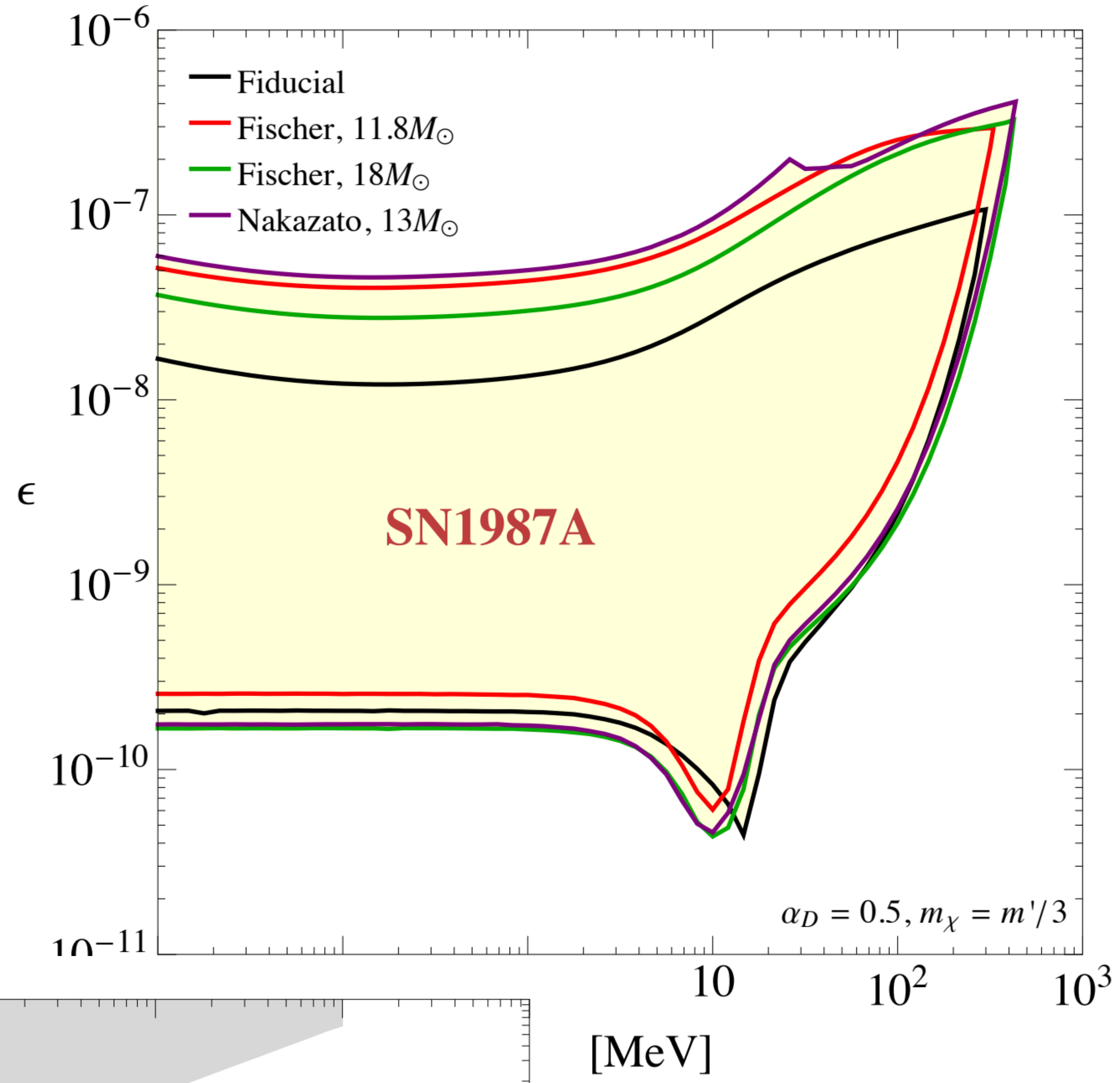
This pressure along with the energy released from the collapse of the core drives a powerful blast wave outward that disrupts the outer parts of the stars completely (this is an area of active research).

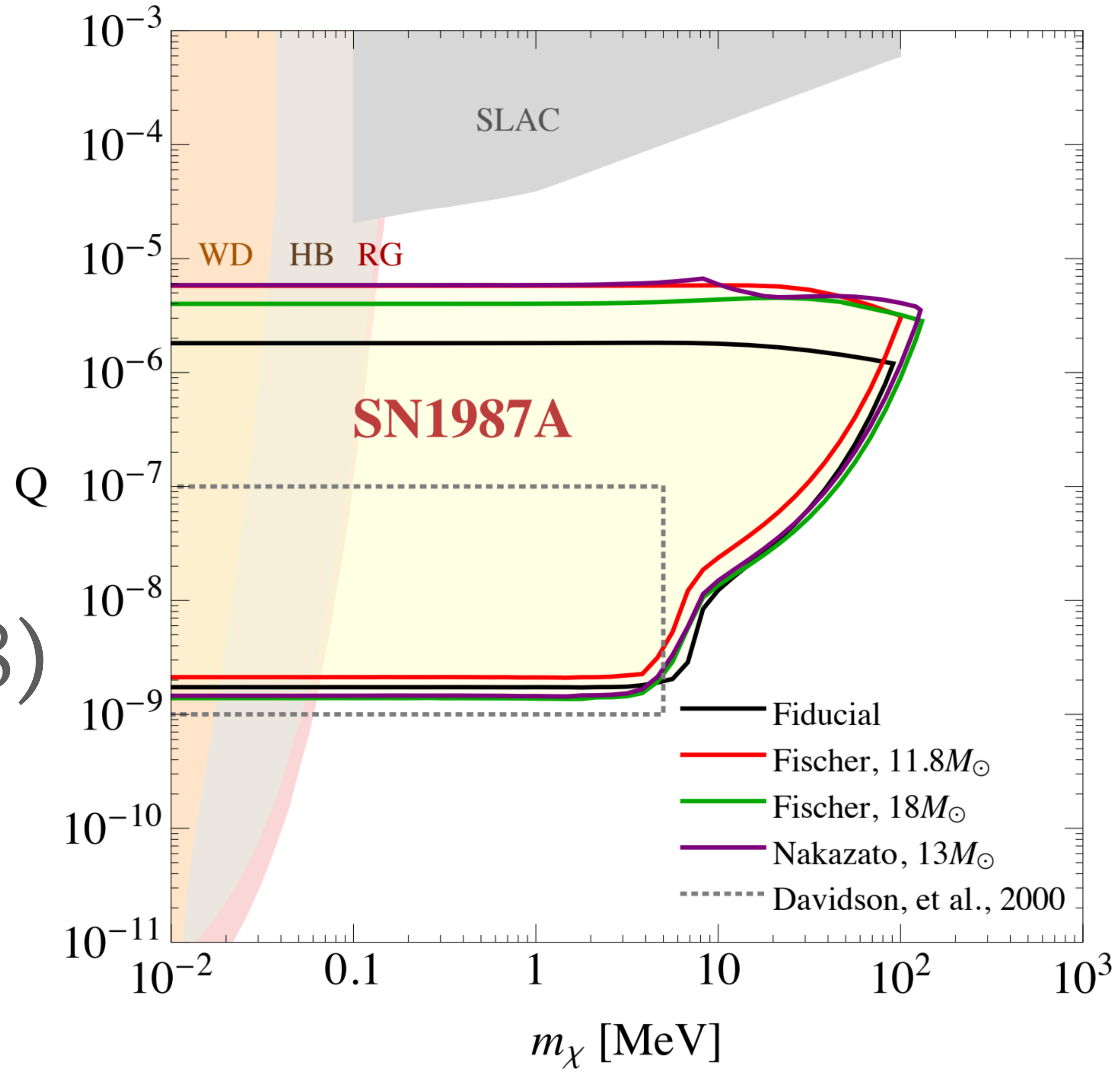
SUPERNOVA 1987A

- Occurred in Large Magellanic Cloud (satellite galaxy of Milky Way) 50 kpc away
- Neutrino experiments saw "burst" of 20 neutrinos (which is a lot for neutrinos!)
- Neutrinos preceded the light by a few hours, dense material surrounding supernova is optically thick to photons but not neutrinos

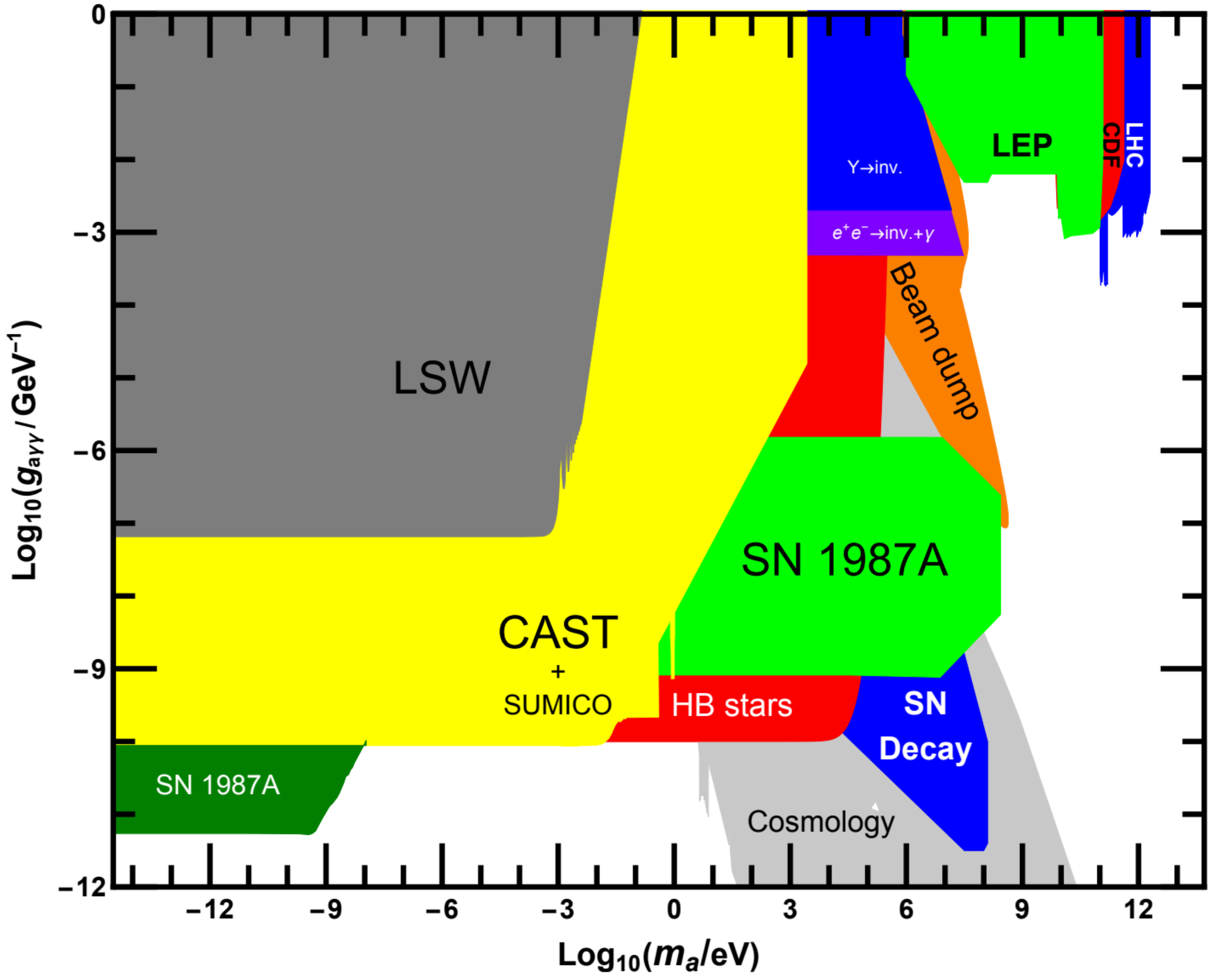
SUPERNOVA 1987A CONSTRAINTS ON BSM





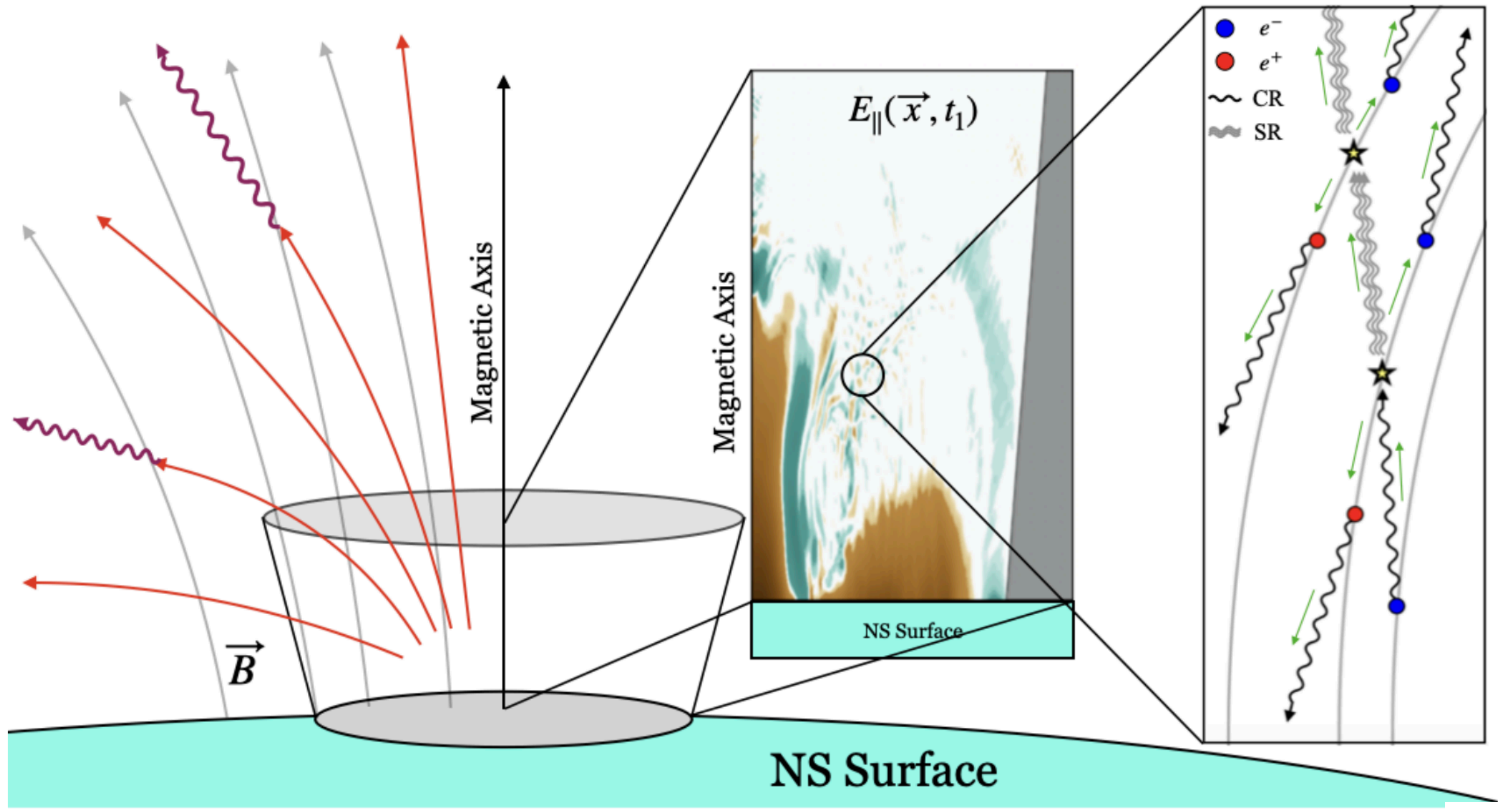


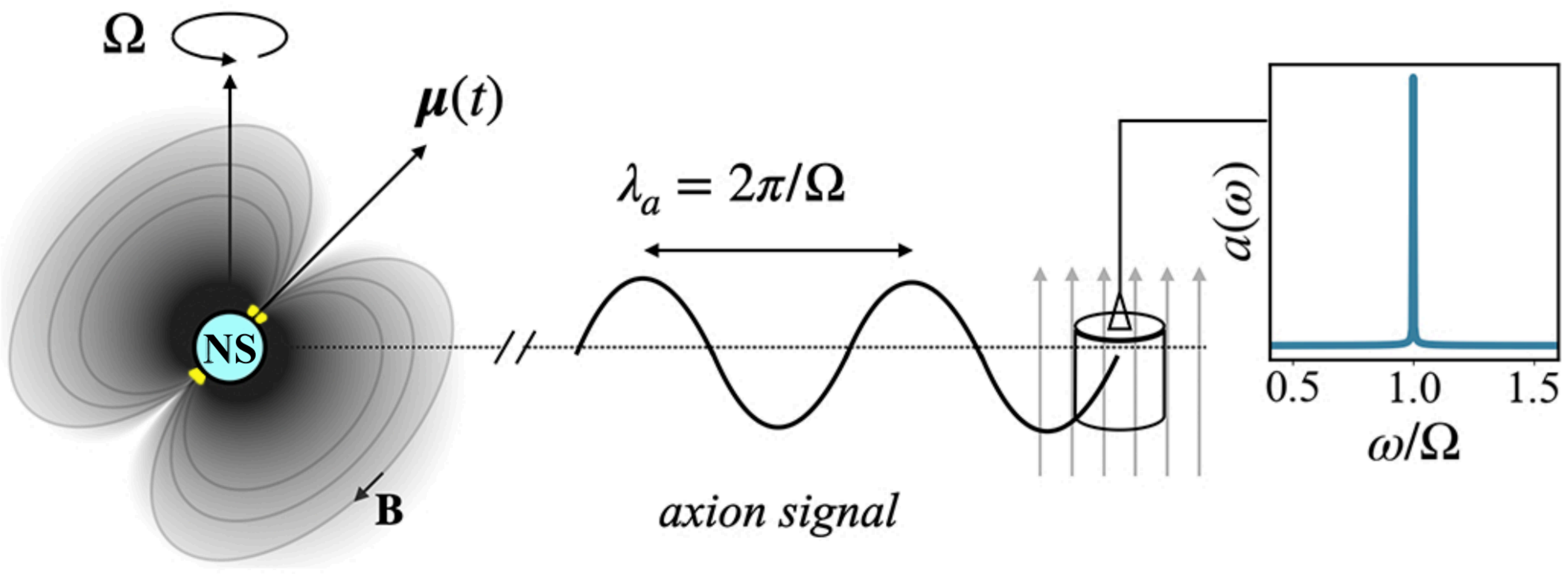
Chang, Essig, McDermott (2018)



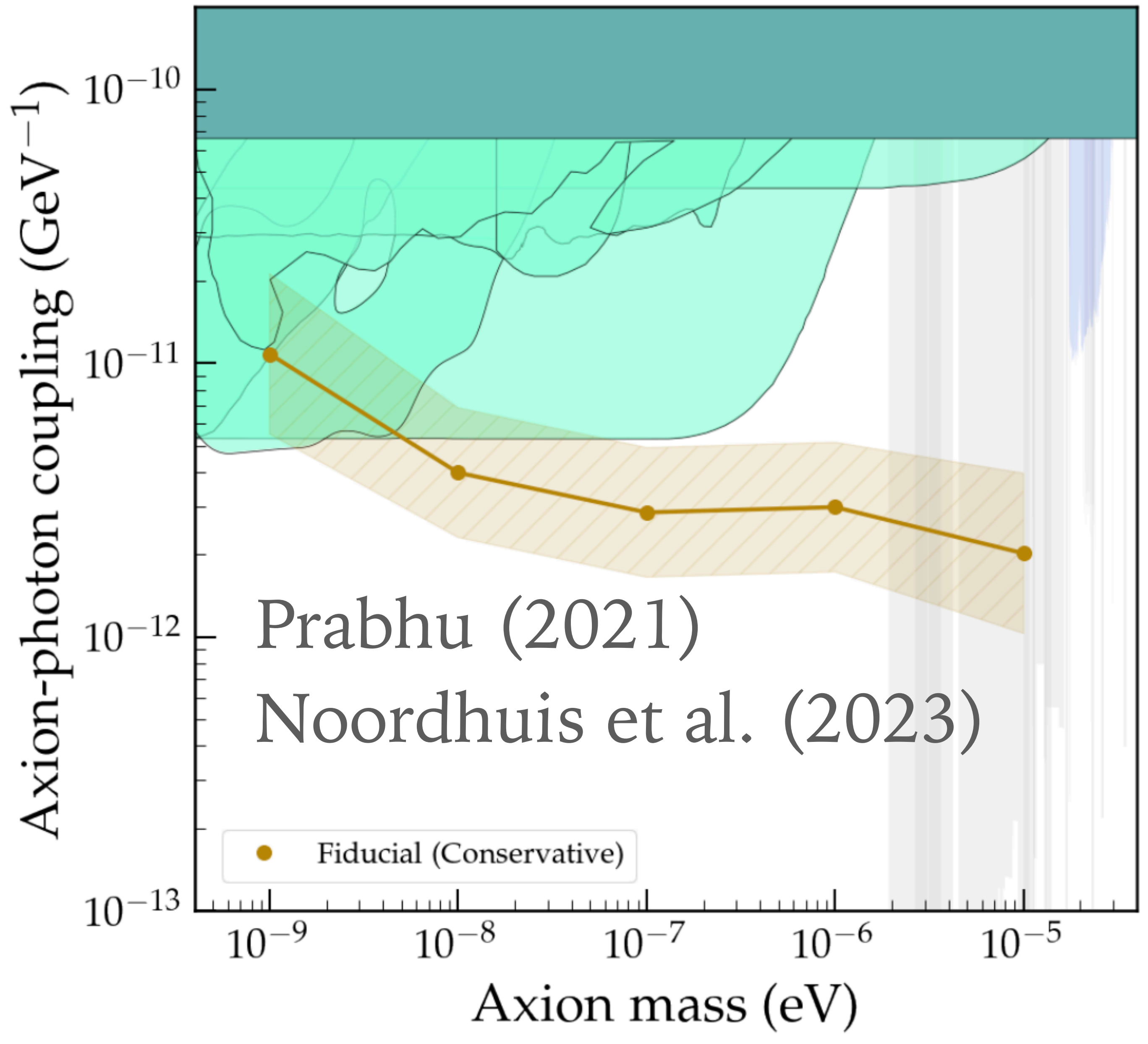
Jaeckel, Malta, Redondo (2017)
cooling + gamma rays from decay!

NEUTRON STAR CONSTRAINTS ON BSM

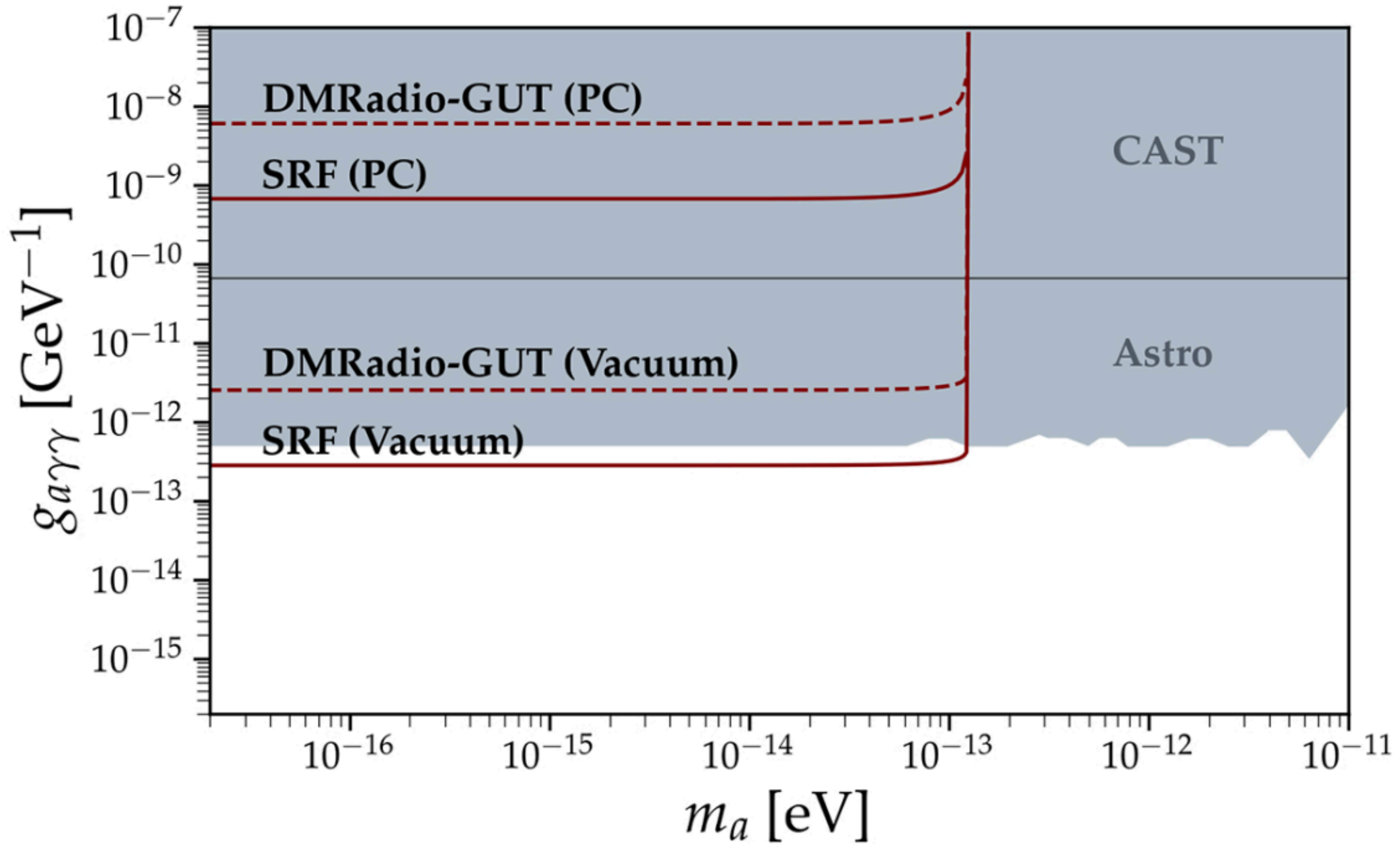


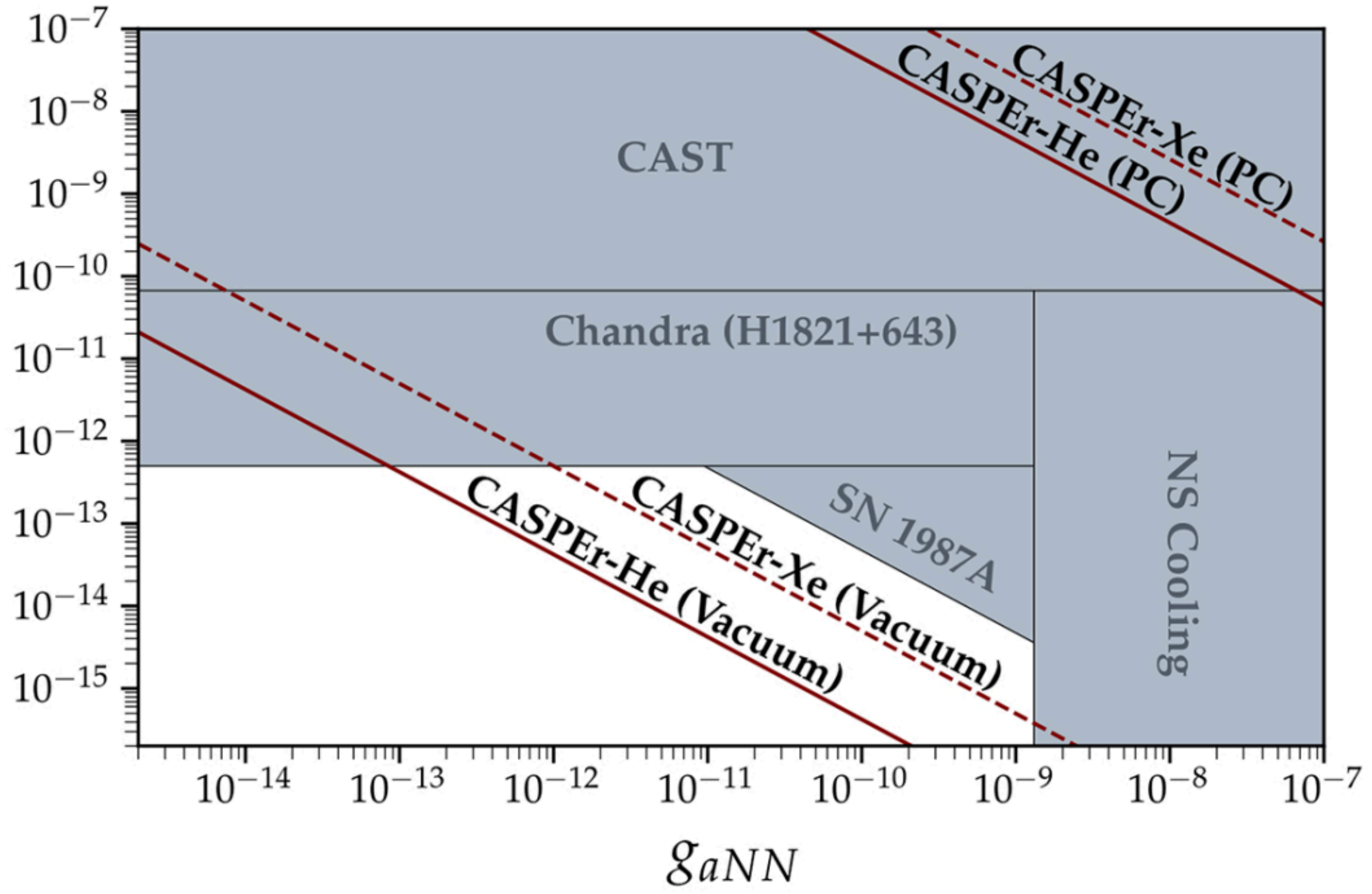


Khelashvili, Lisanti, Prabhu, Safdi (2024)

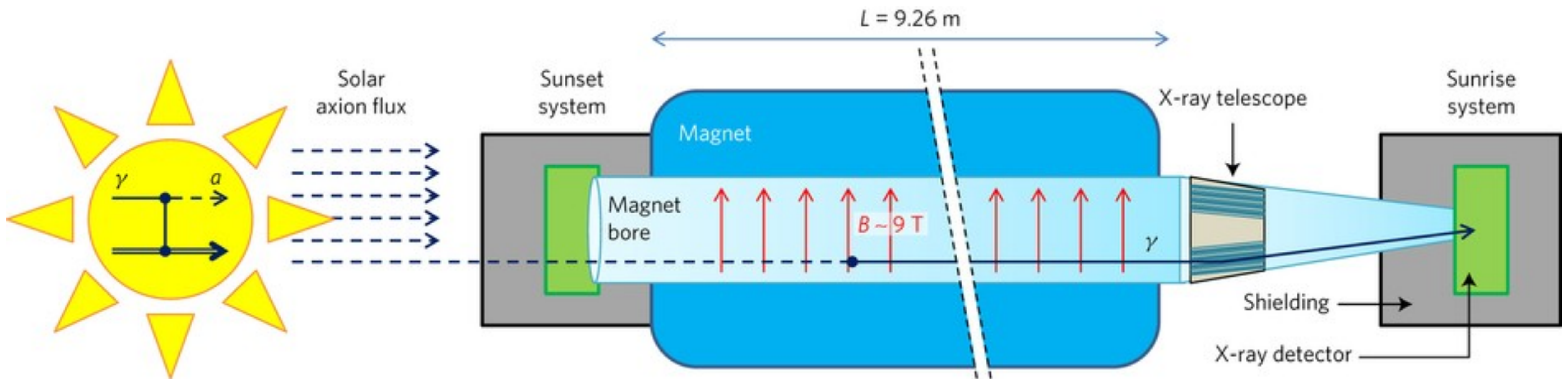


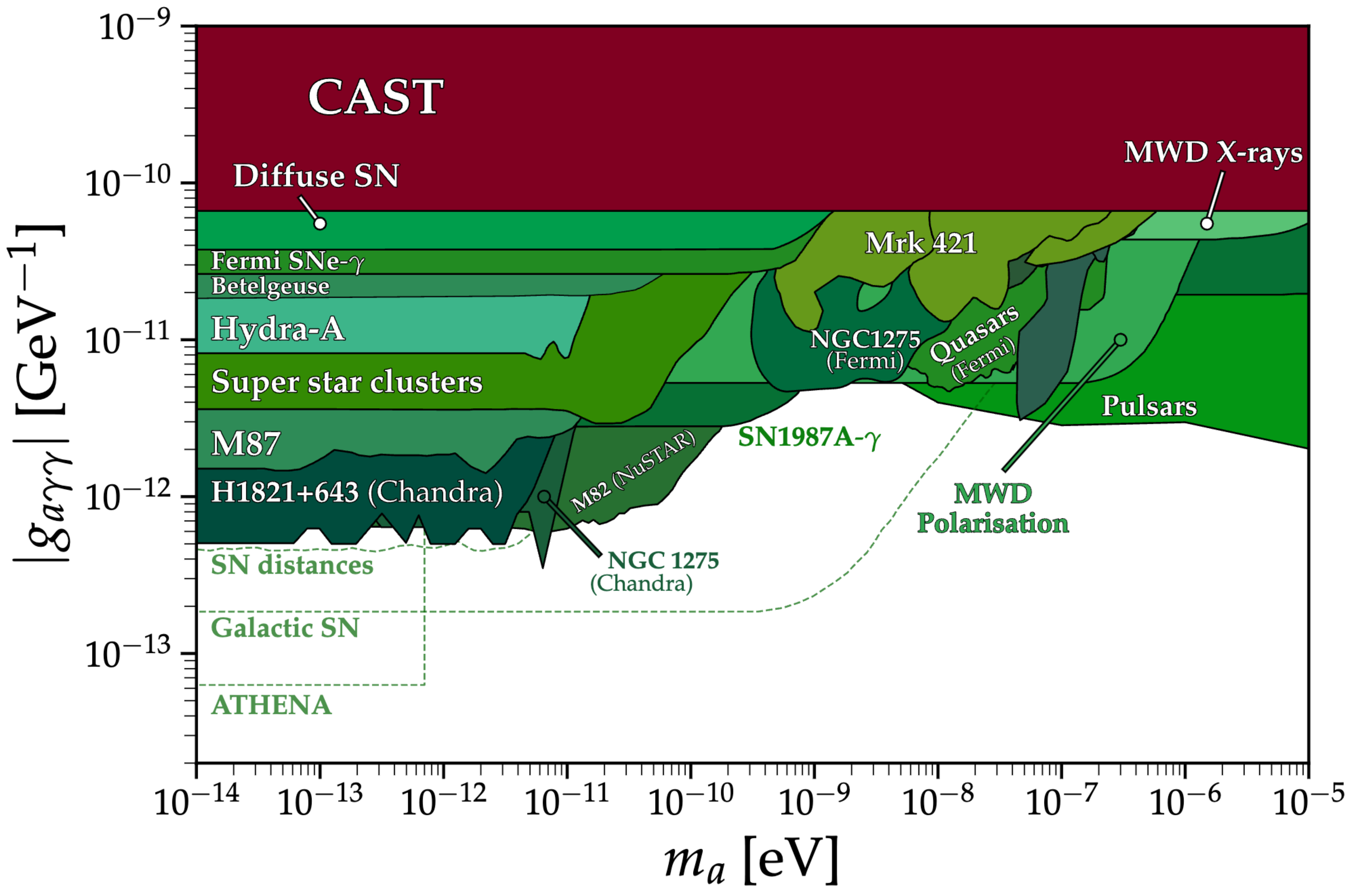
Prabhu (2021)
Noordhuis et al. (2023)

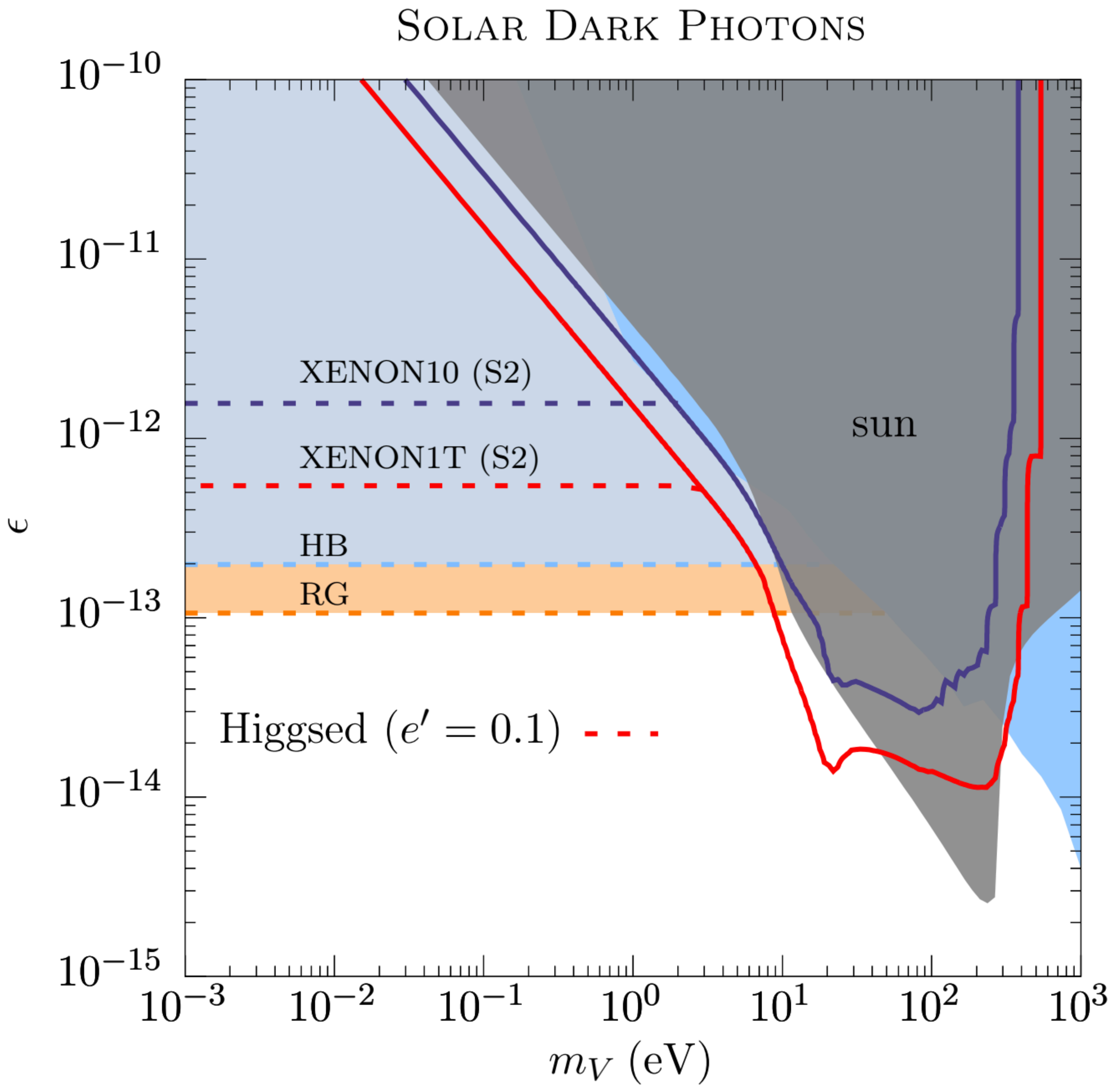




LOOKING FOR SOLAR BYPRODUCTS ON EARTH

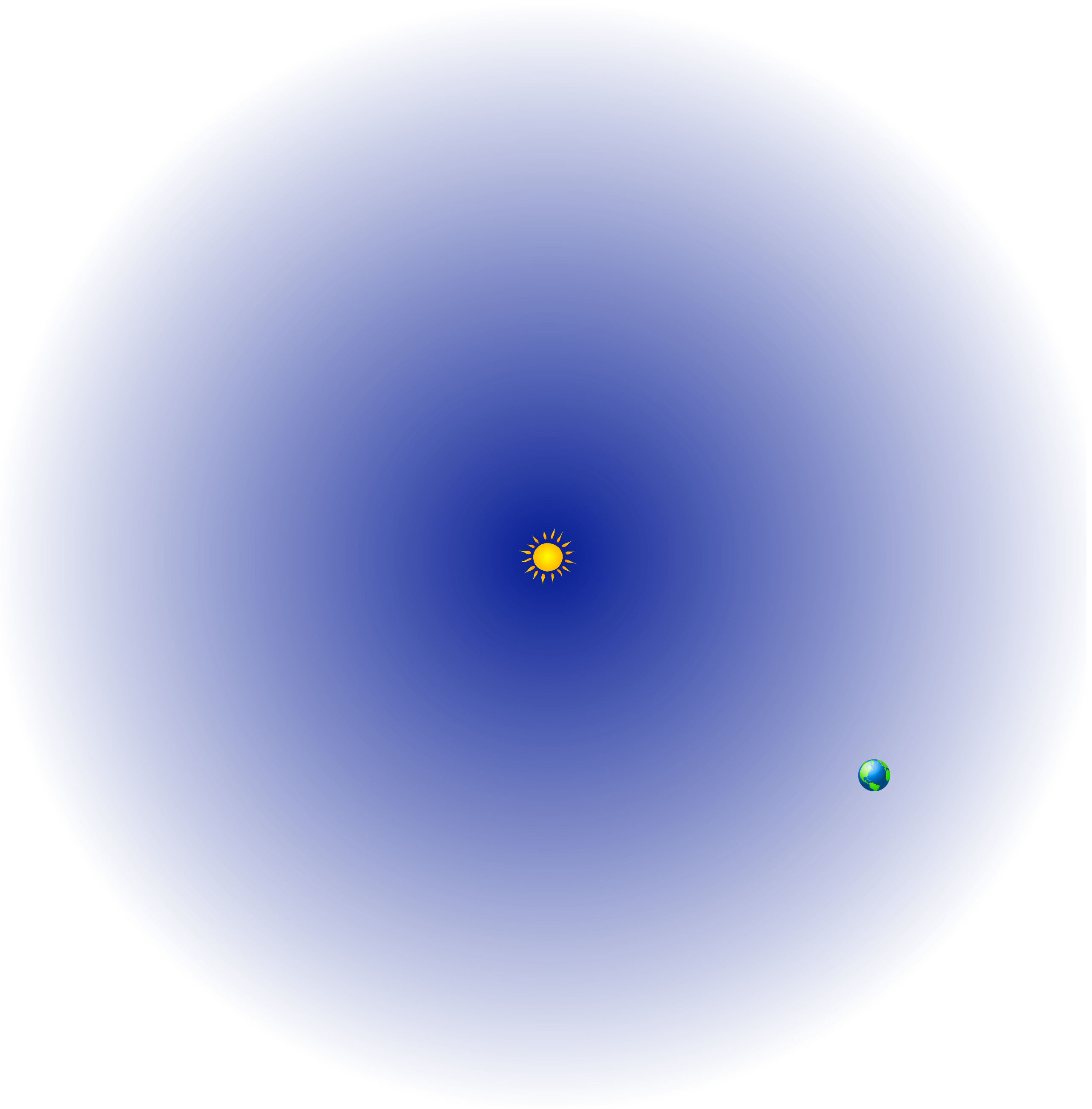




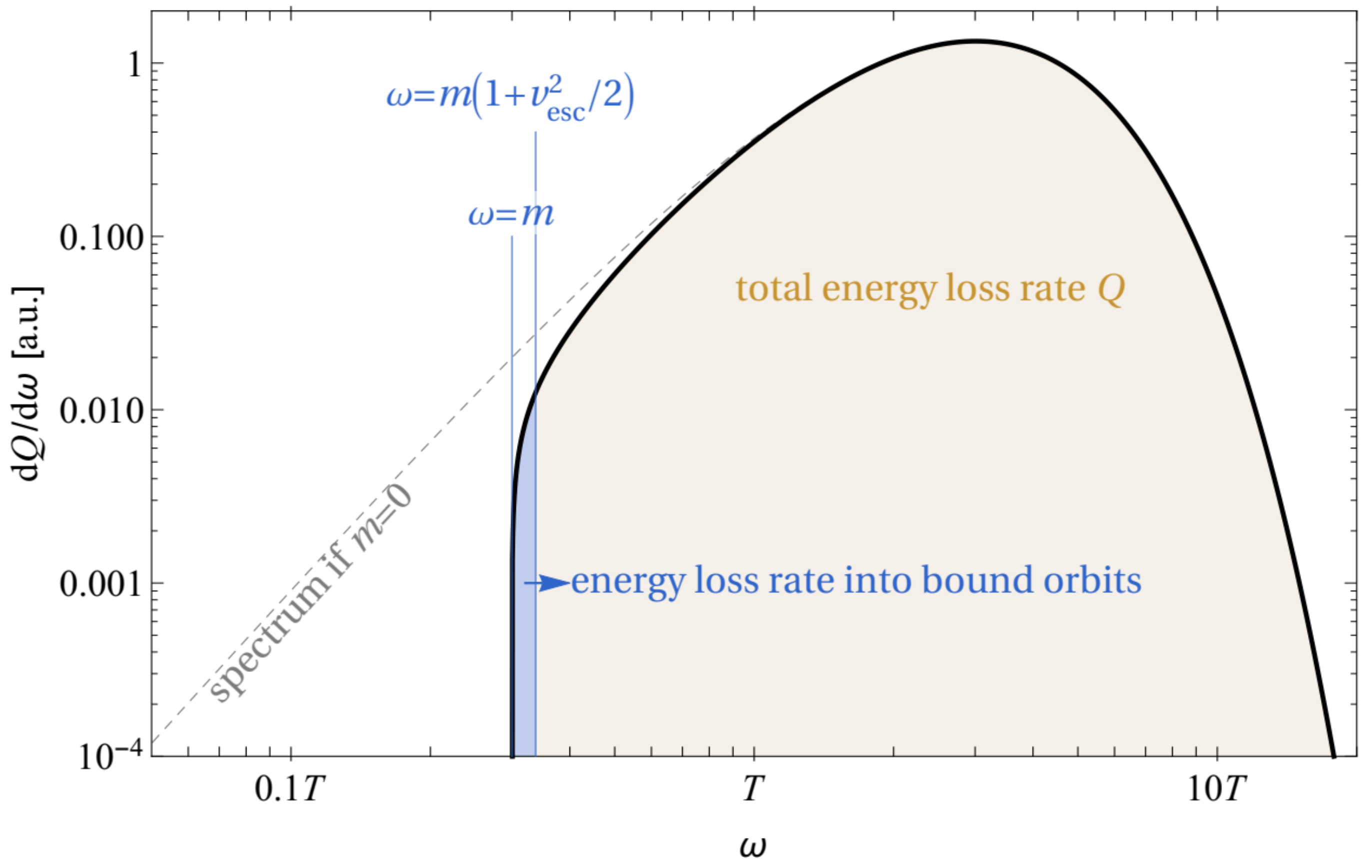


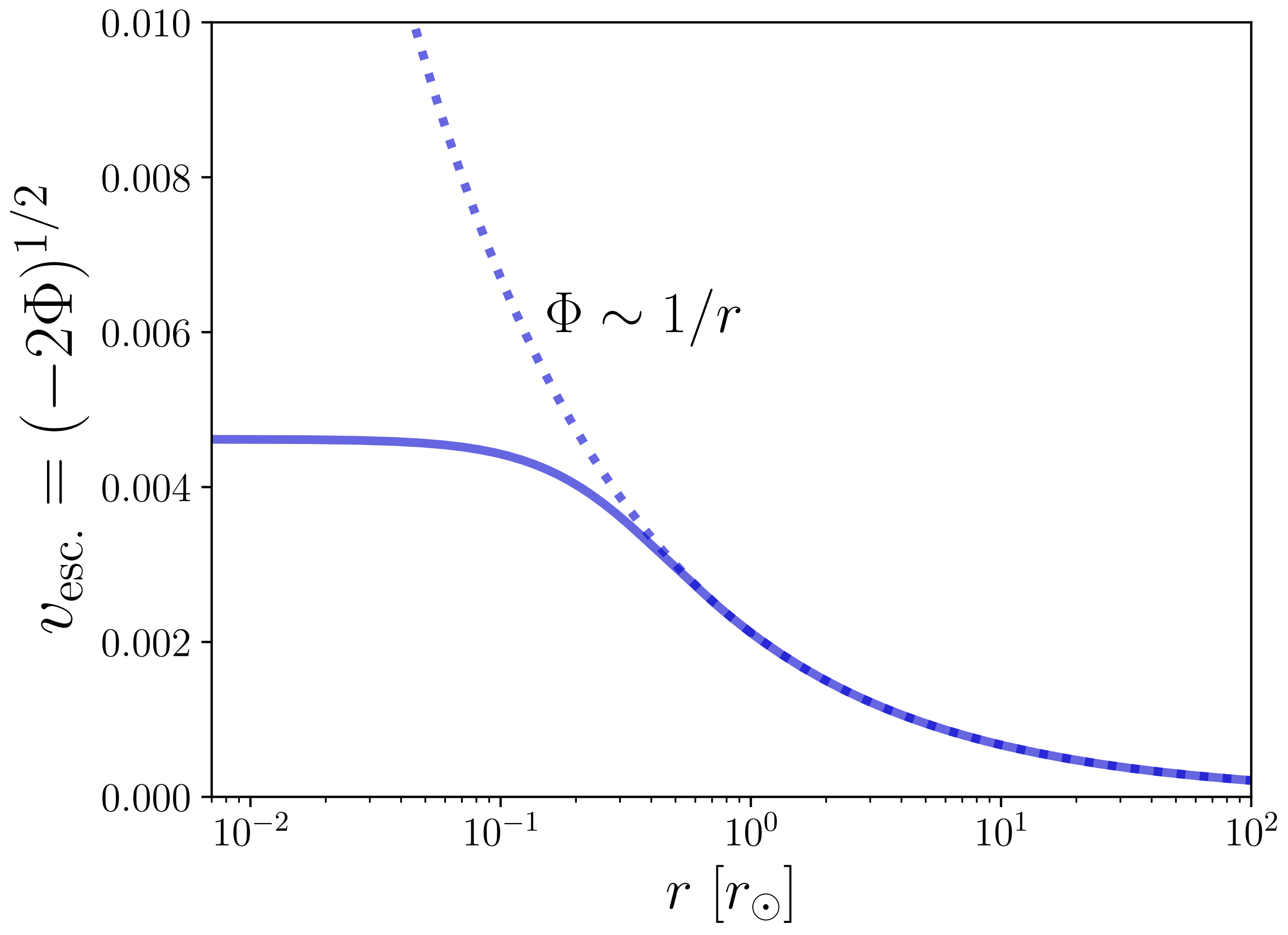
An, Pospelov, Pradler, Ritz (2020)

SOLAR BASINS OF PARTICLES TRAPPED BY GRAVITY



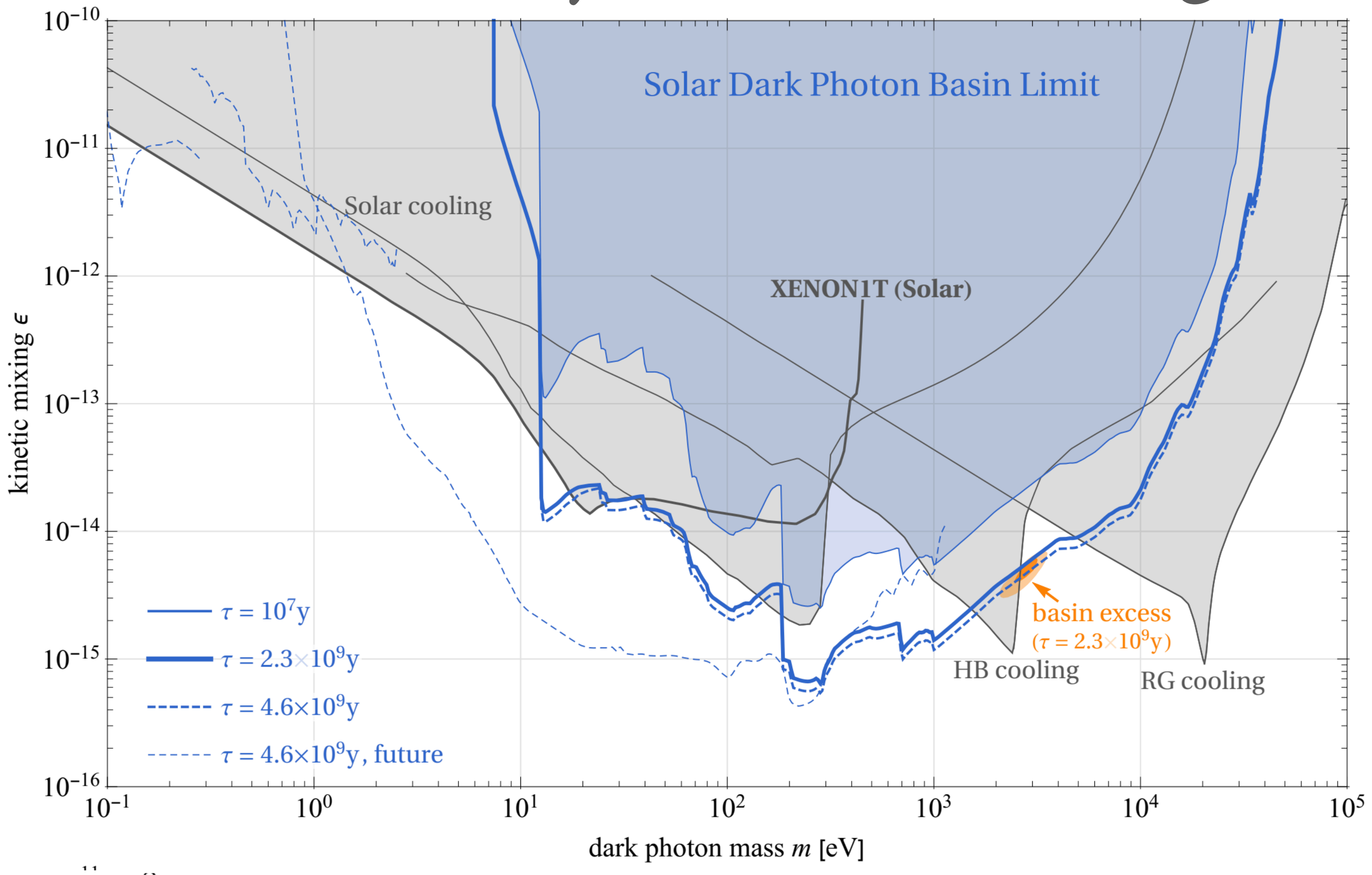
(not to scale)

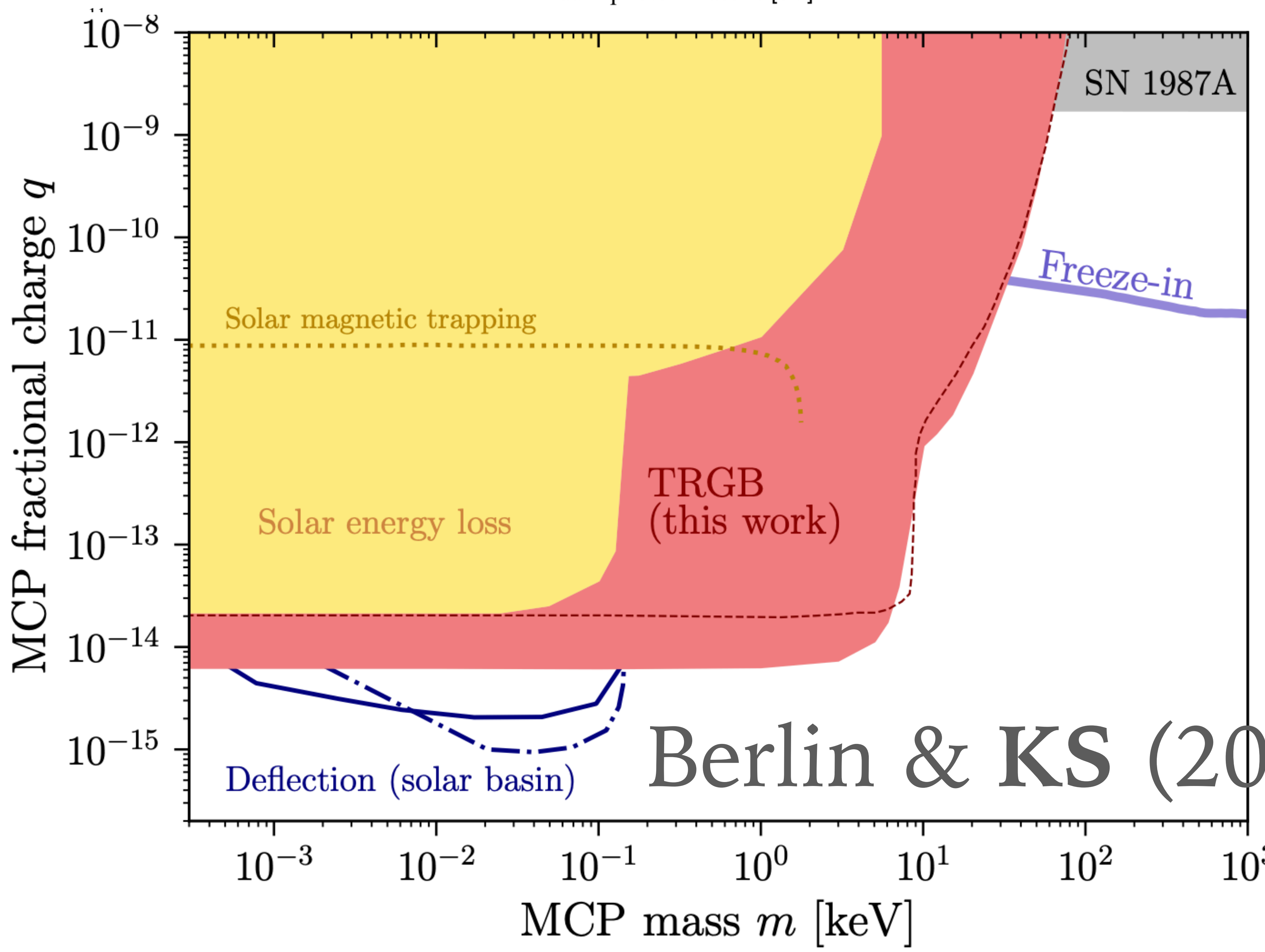




Van Tilburg (2020)

Lasenby & Van Tilburg (2020)





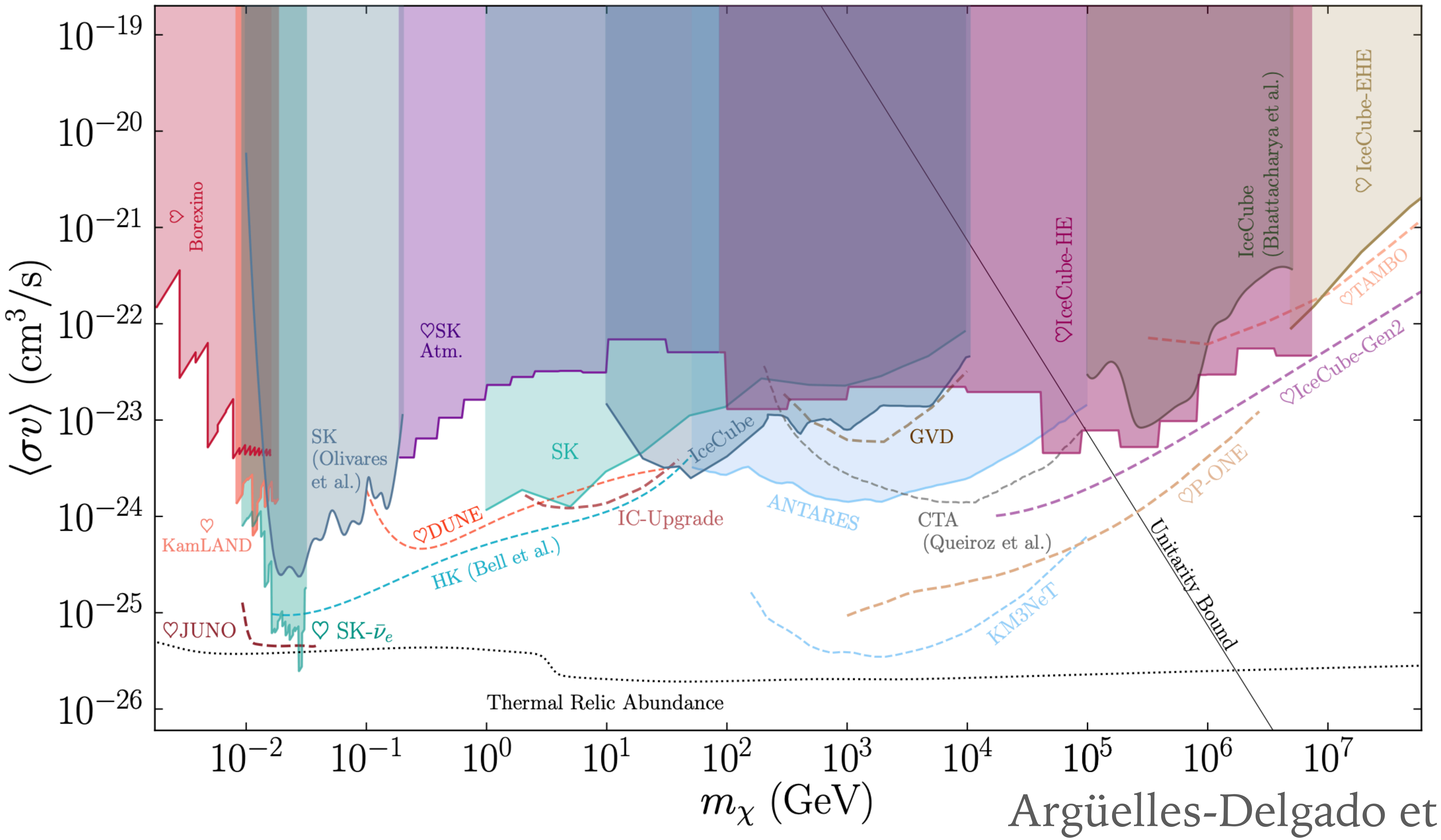
Berlin & **KS** (2021)

TOPIC #2: BREAK IT

MODEL SYSTEM: GALAXIES AND THE INTERGALACTIC MEDIUM

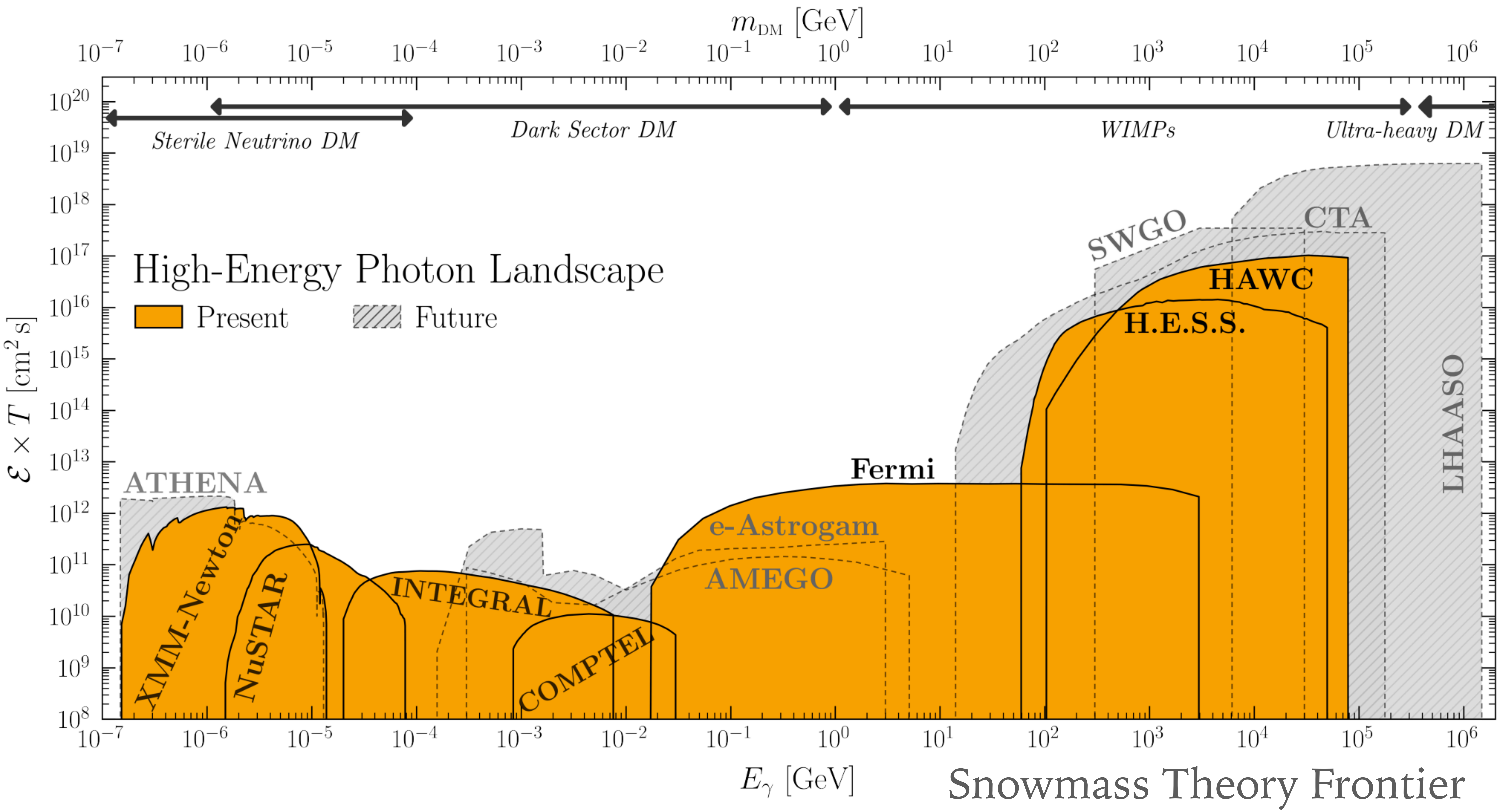
More in-depth reading: Tracy Slatyer's TASI notes

NEUTRINOS ARE DIFFICULT



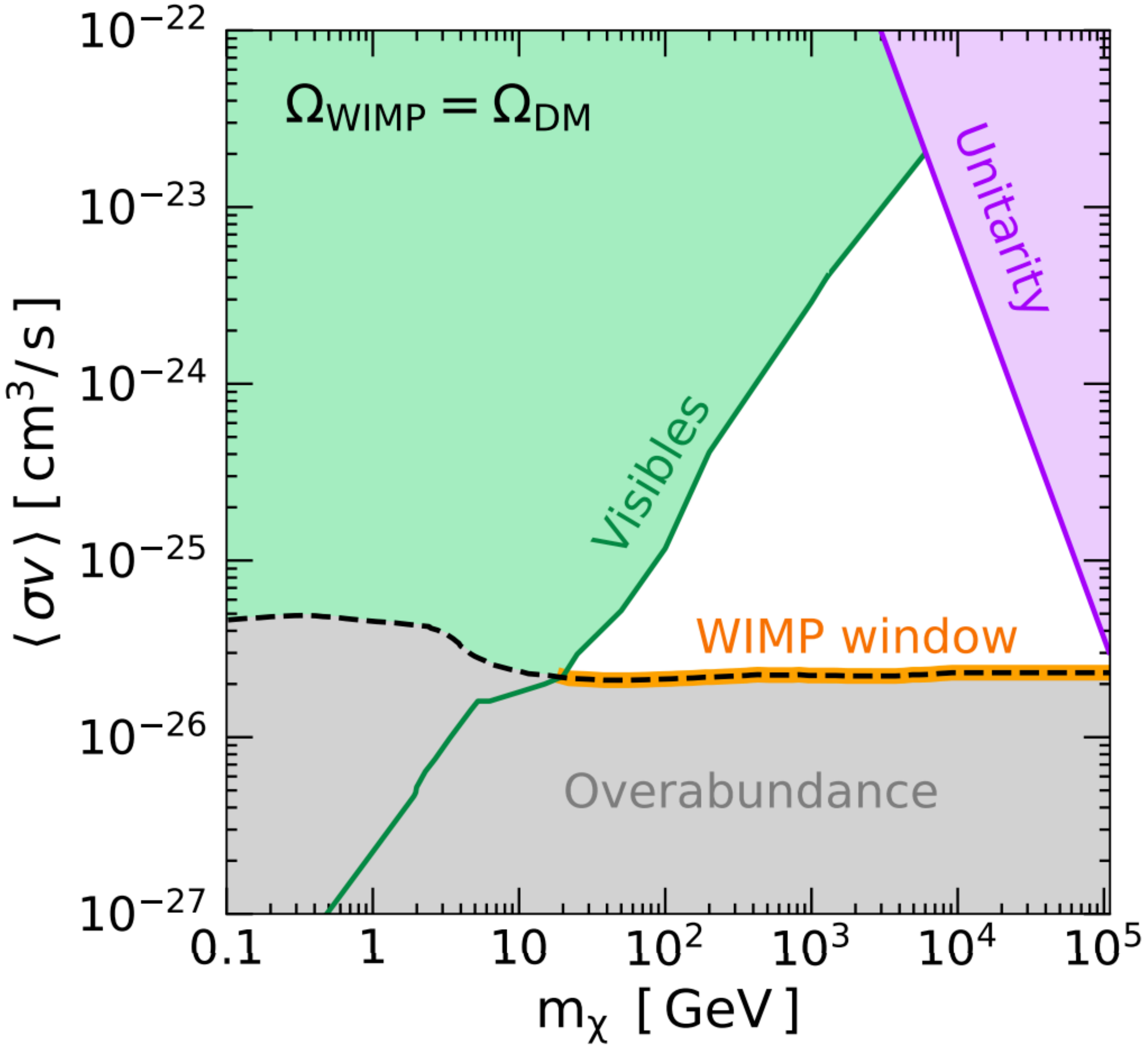
Argüelles-Delgado et al. (2021)

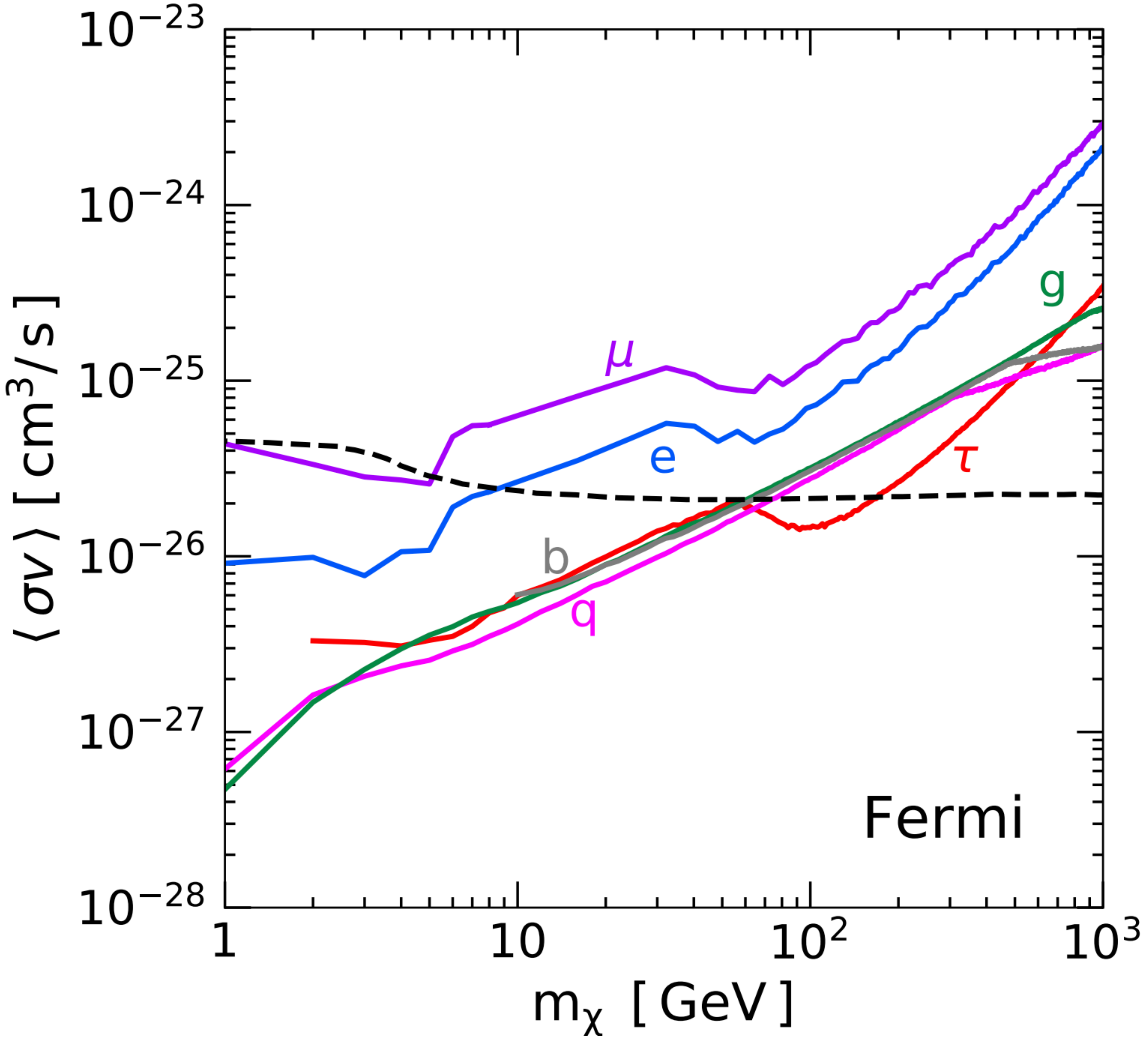
MENU OF TELESCOPE OPTIONS



Snowmass Theory Frontier

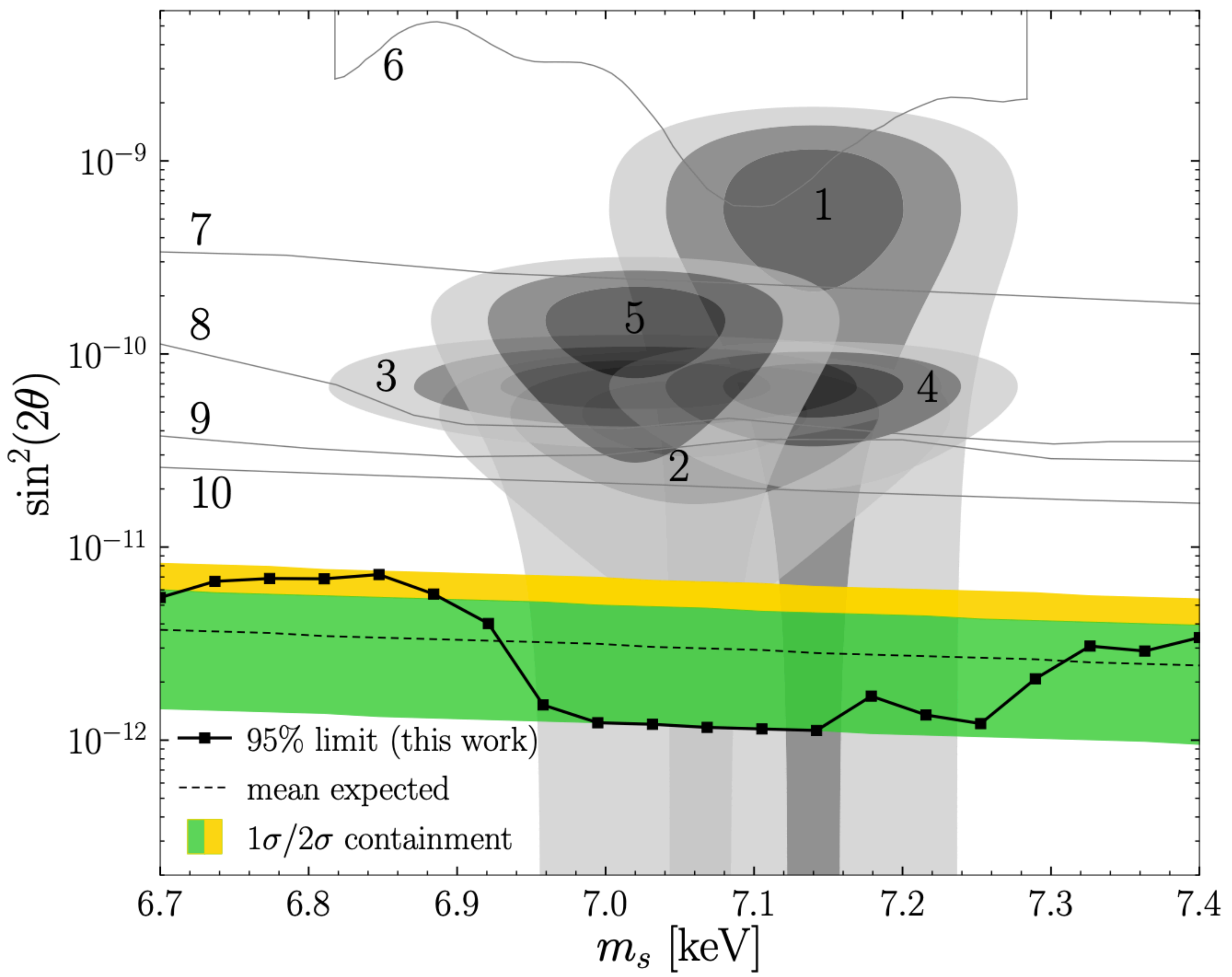
CONSTRAINTS ON WIMP ANNIHILATION TO VISIBLES



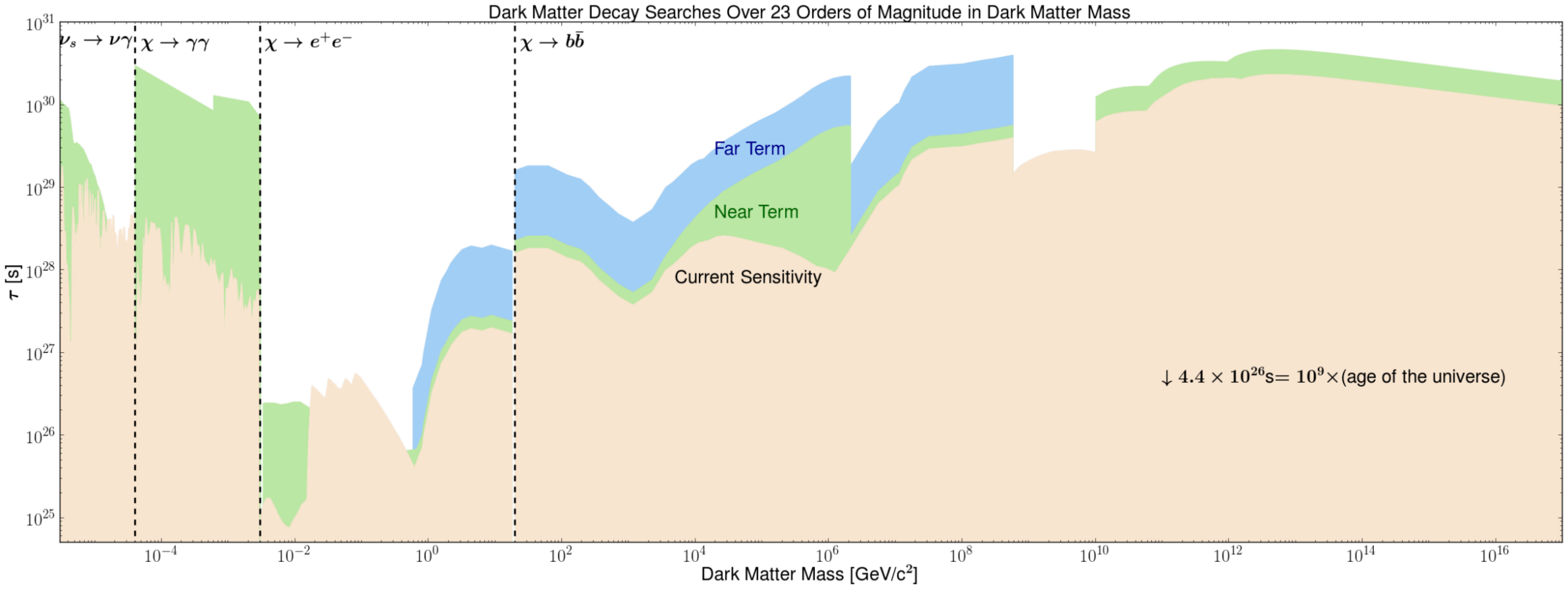


Leane et al. (2018)

DECAYING DARK MATTER CONSTRAINTS

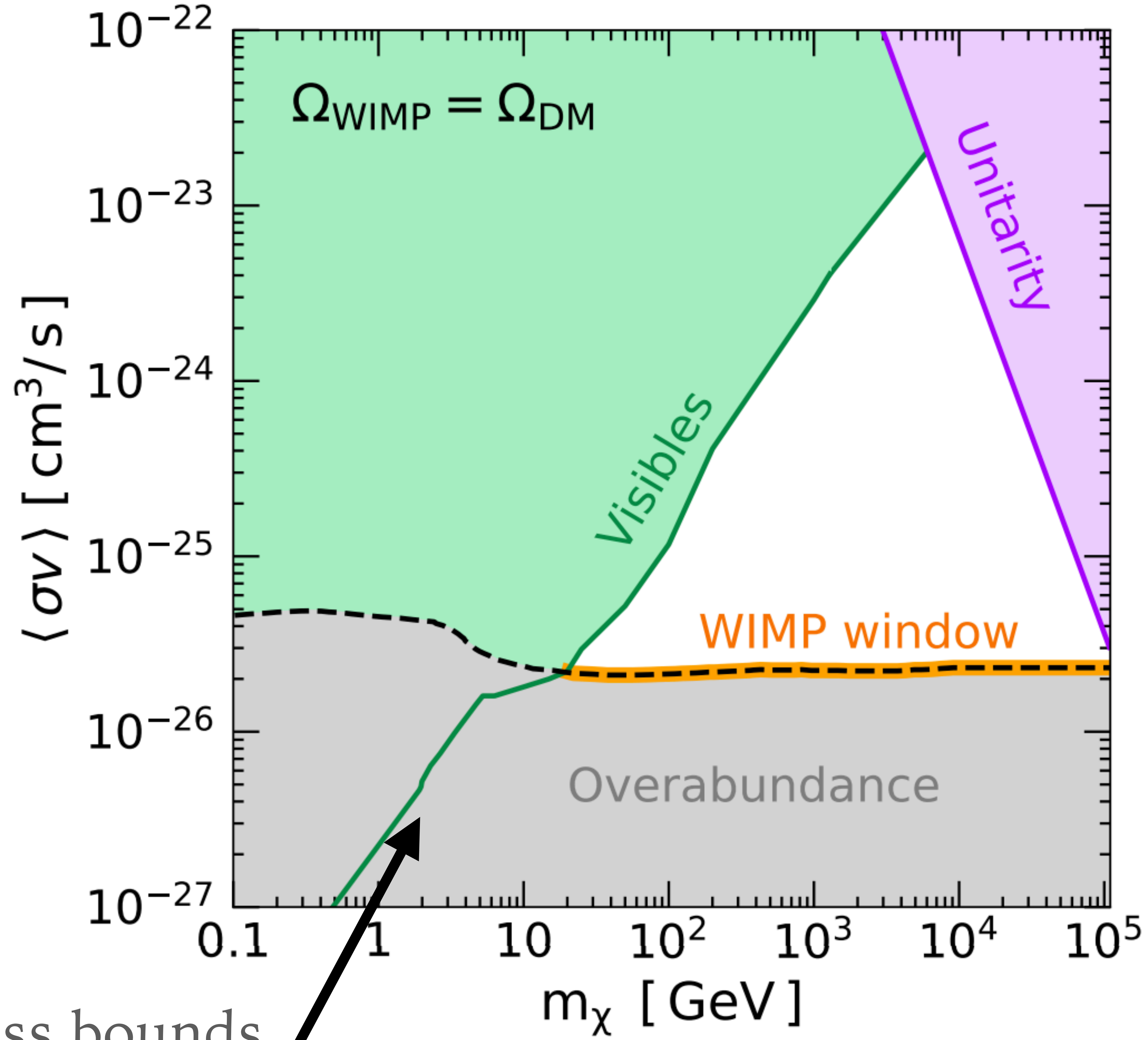


Dessert, Rodd, Safdi (2020)

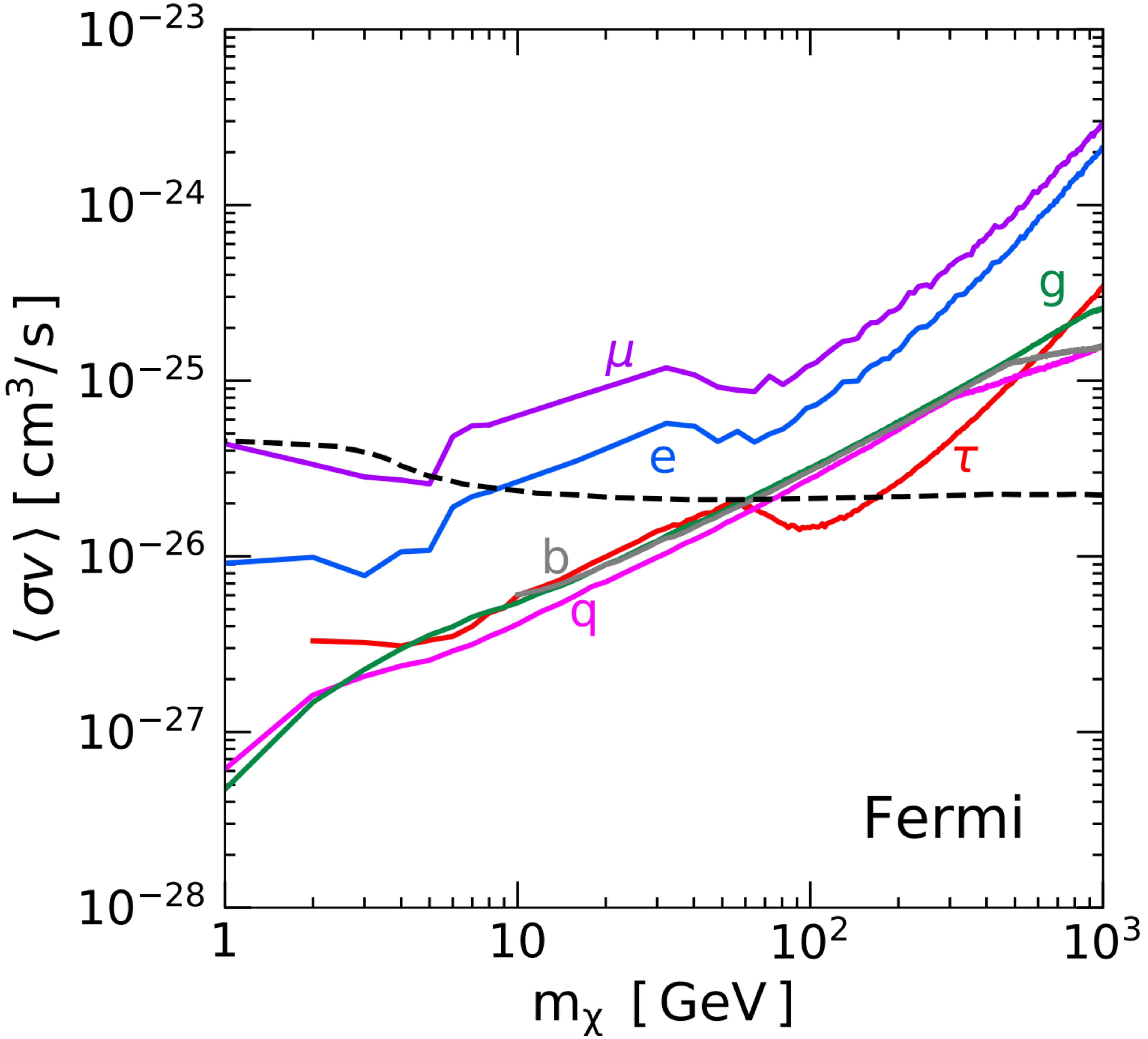


Snowmass Topical Group on Particle Dark Matter

CONSTRAINTS ON WIMP ANNIHILATION TO VISIBLES



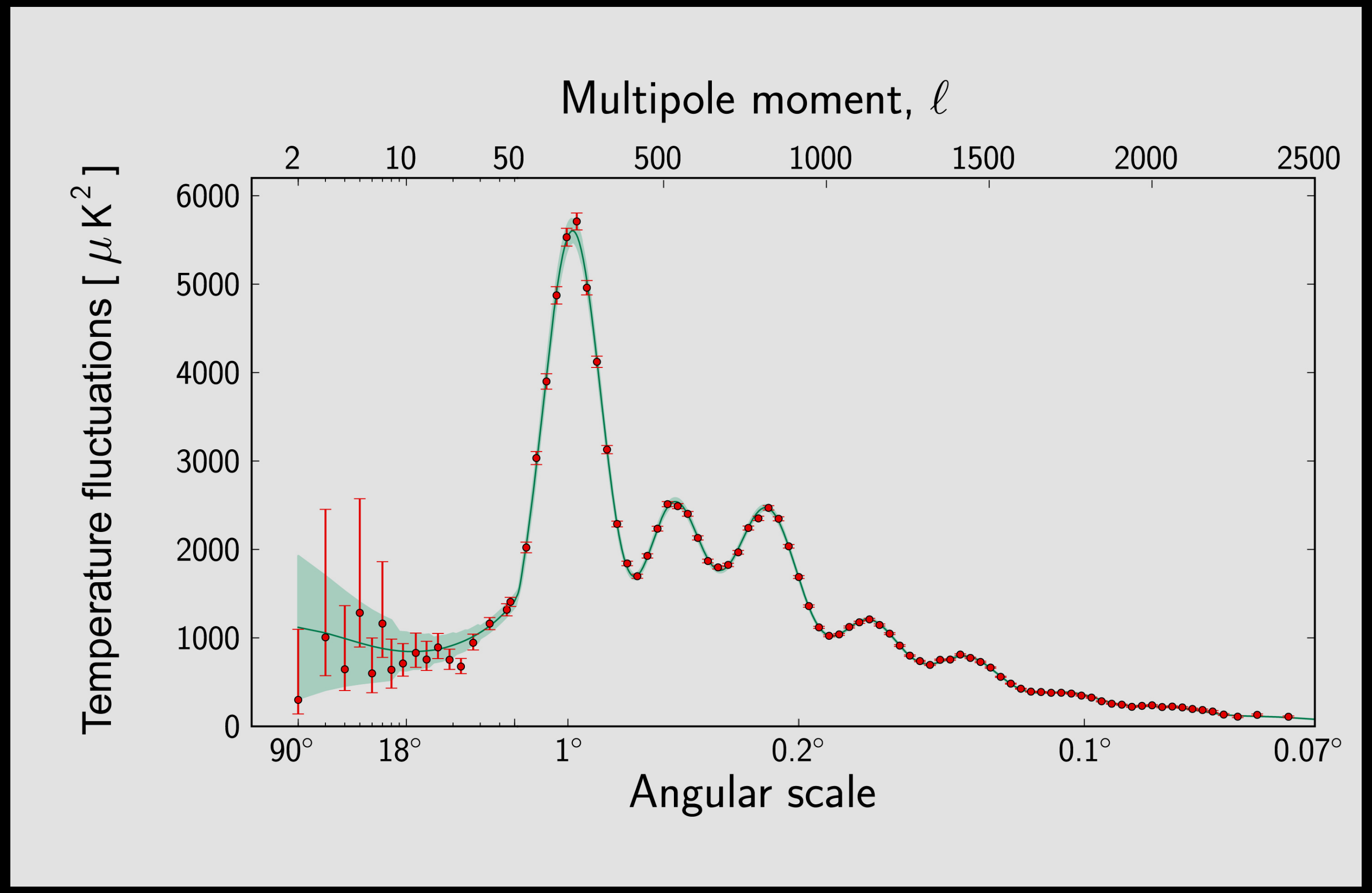
Low-mass bounds are driven by CMB

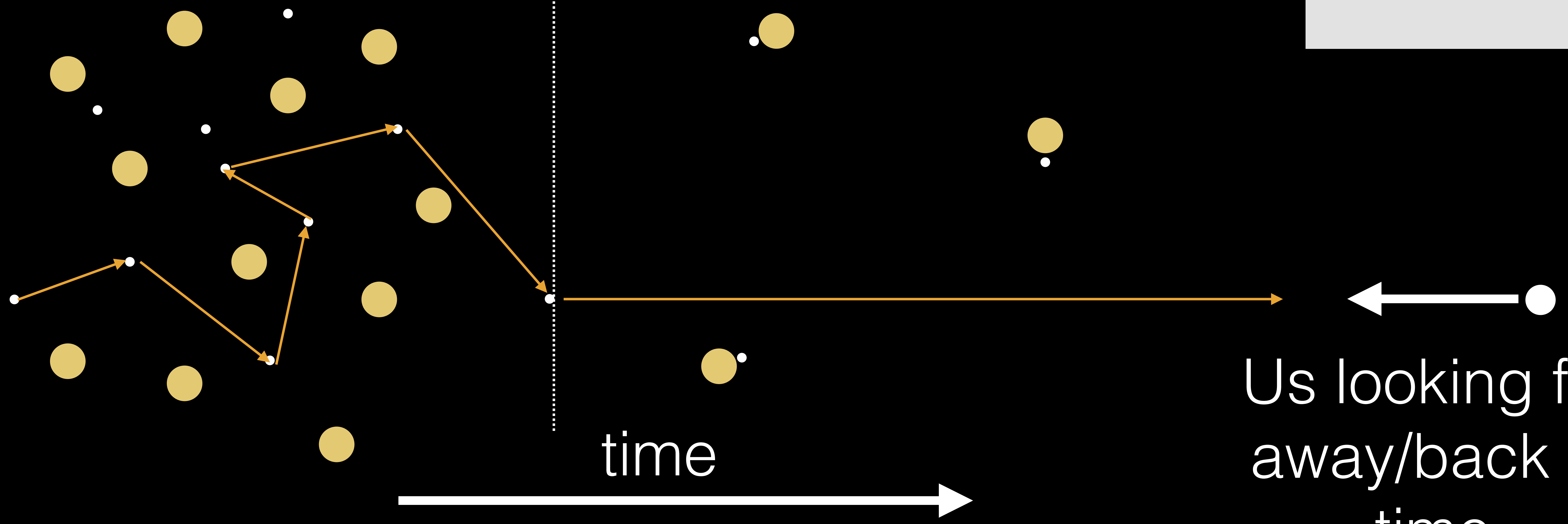


Leane et al. (2018)

Too hot for atoms to form (plasma)
Not transparent

Cool enough for atoms to exist
Transparent





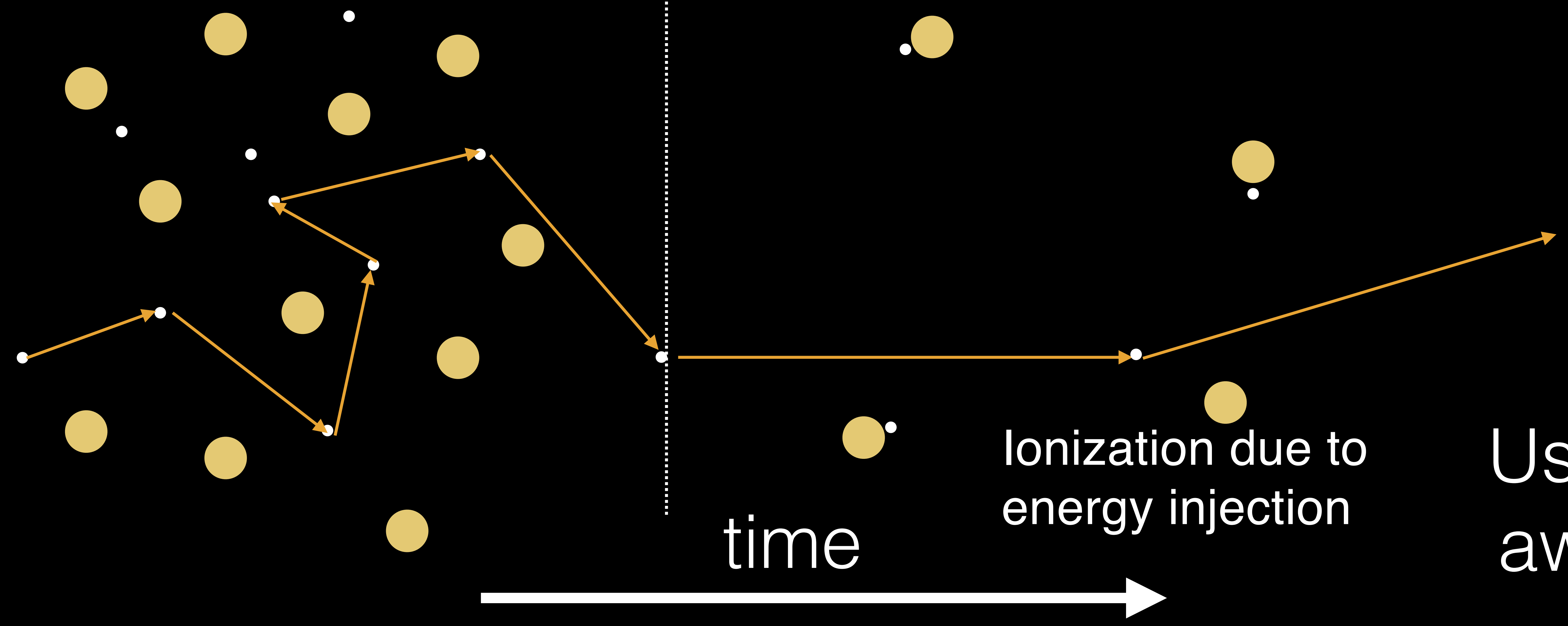
Us looking far away/back in time

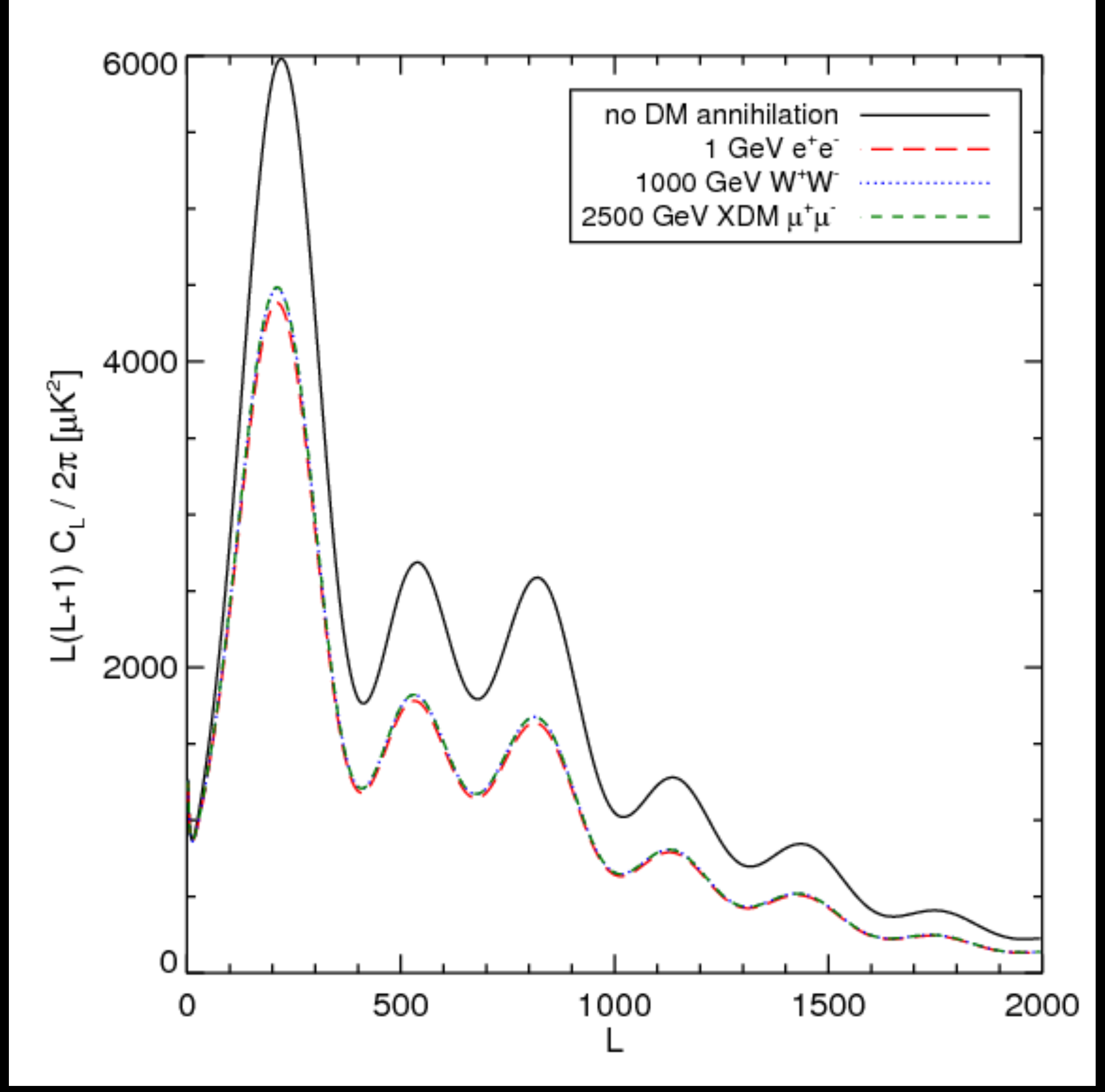
Smaller
Denser
Hotter

Larger
Less dense
Cooler

Too hot for atoms to form (plasma)
Not transparent

Cool enough for atoms to exist
Transparent





Ionization due to energy injection

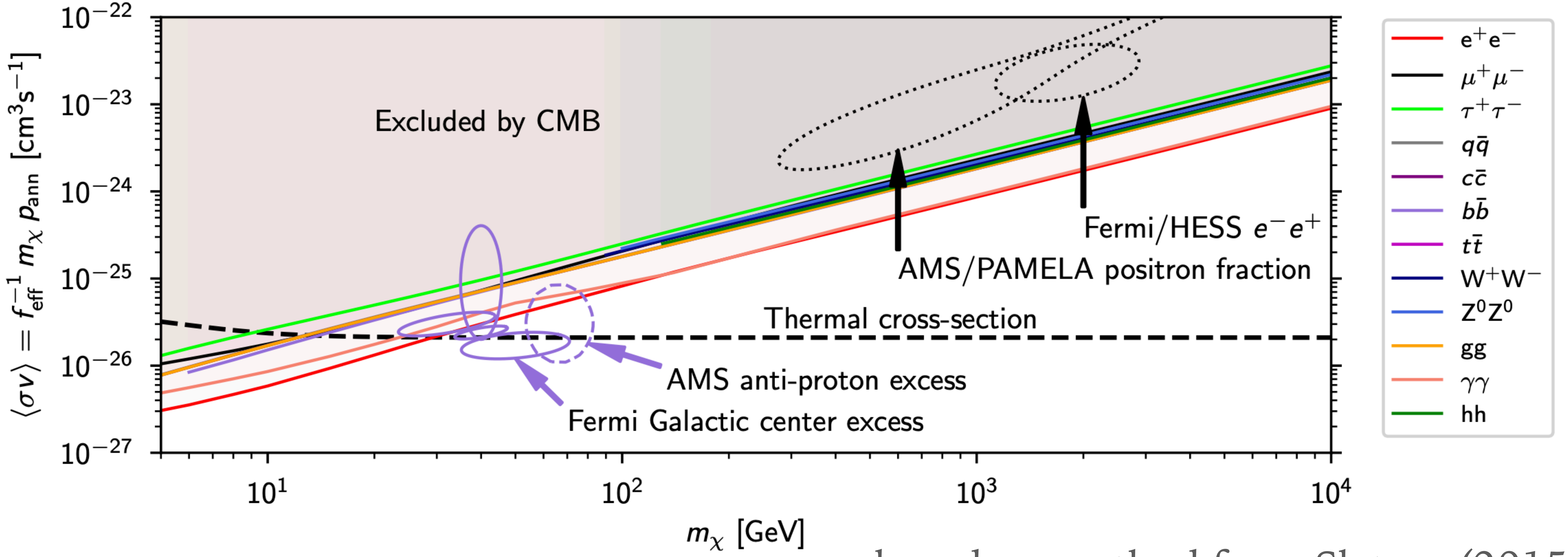
time

Us looking far away/back in time

Smaller
Denser
Hotter

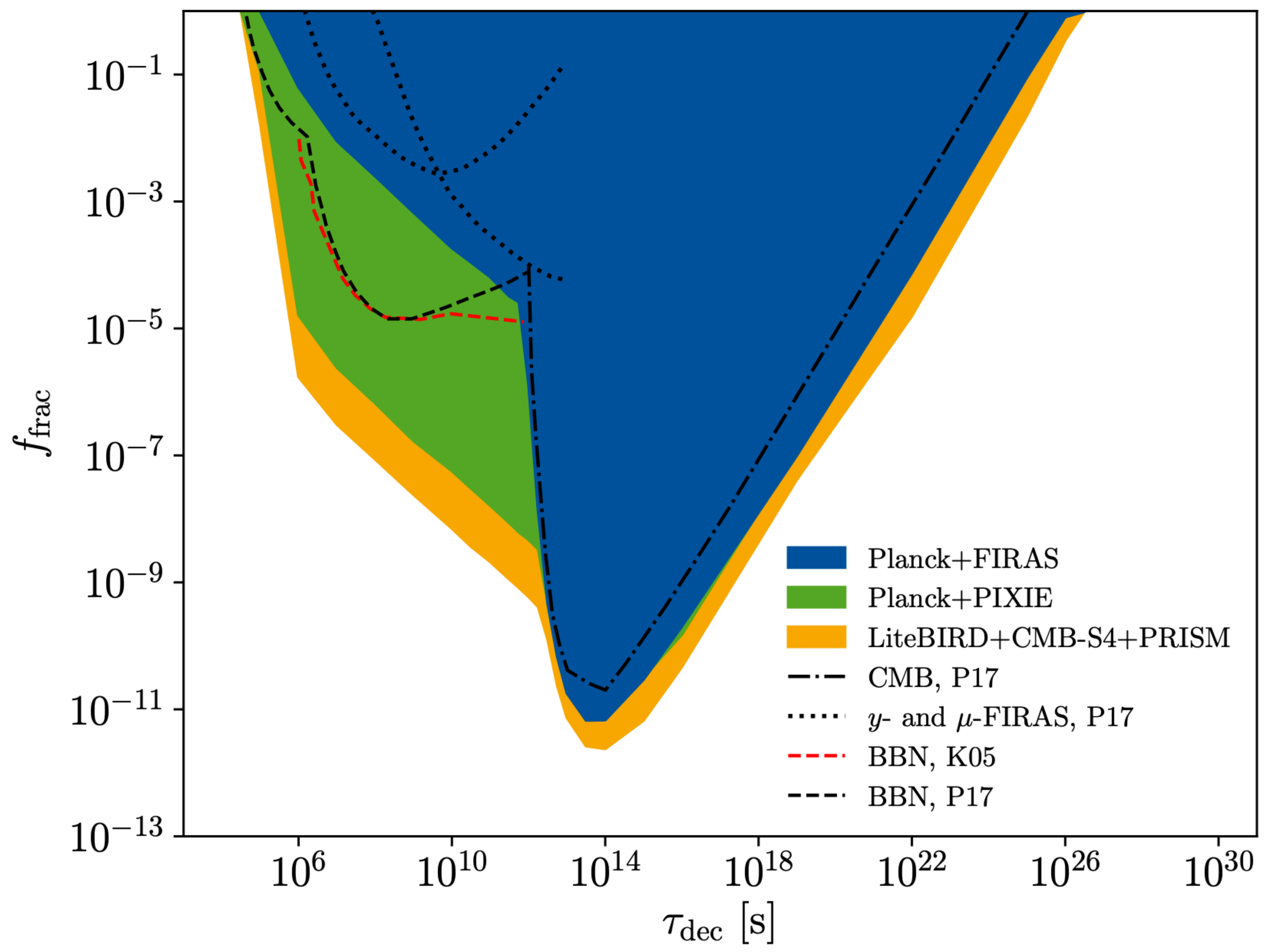
Larger
Less dense
Cooler

PLANCK 2018 CONSTRAINTS ON ANNIHILATION

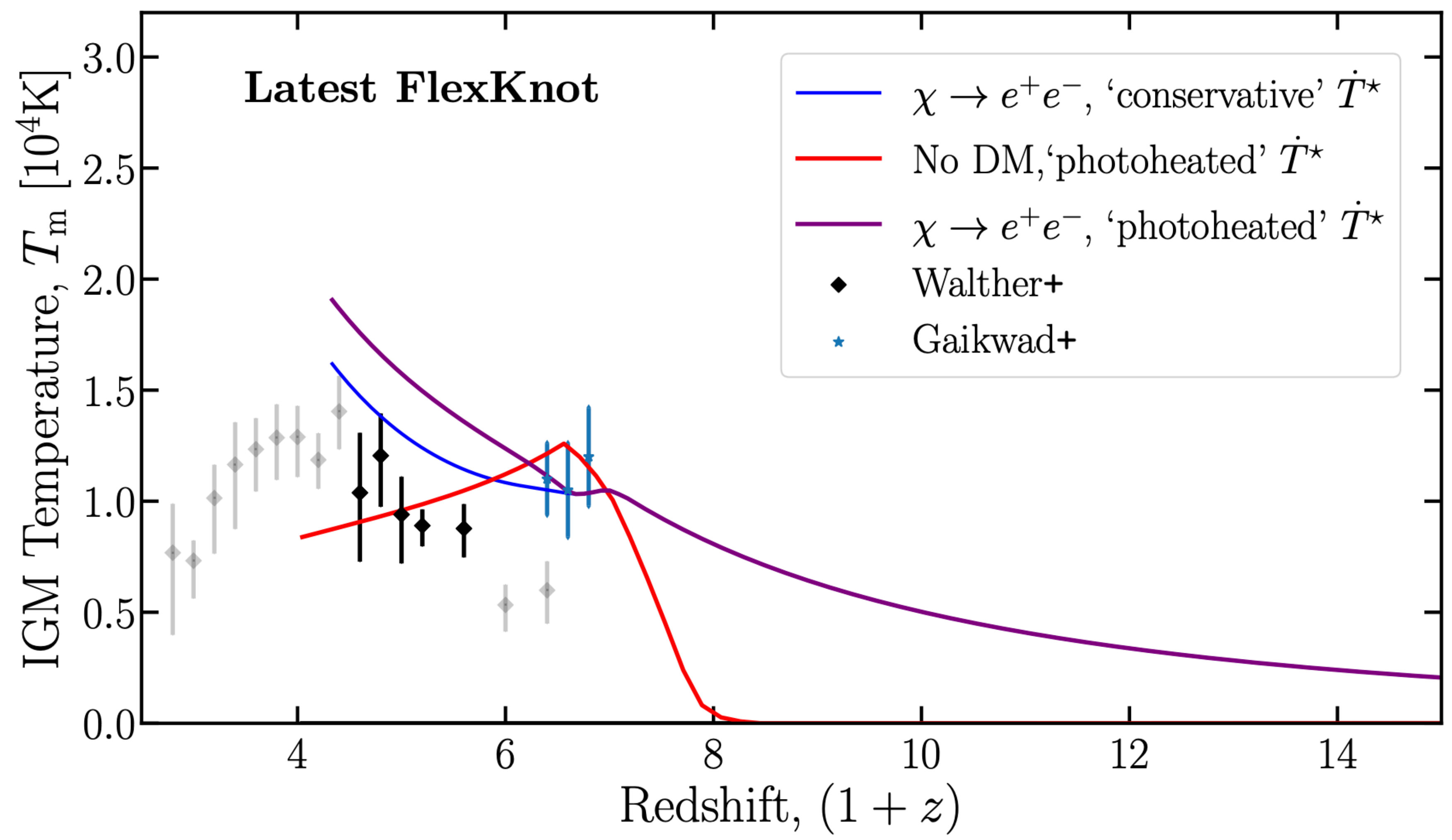


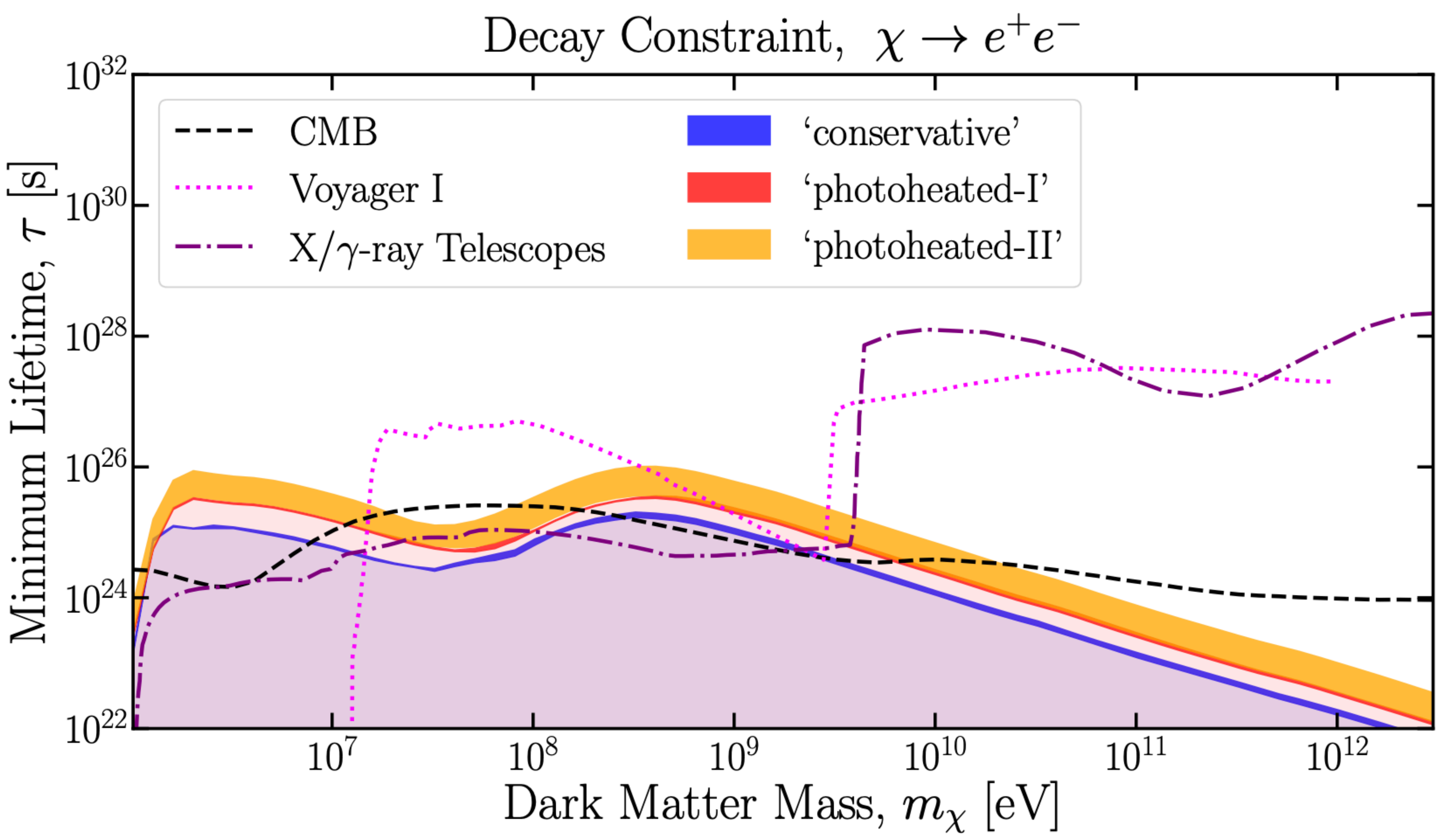
based on method from Slatyer (2015a, 2015b)

IGM CONSTRAINTS ON DECAYING DARK MATTER



Lucca, Schöneberg, Hooper, Lesgourges, Chluba (2020)





Liu, Qin, Ridgway, Slatyer (2020)

TOPIC #3: SHAKE IT

MODEL SYSTEM: DARK MATTER HALOS

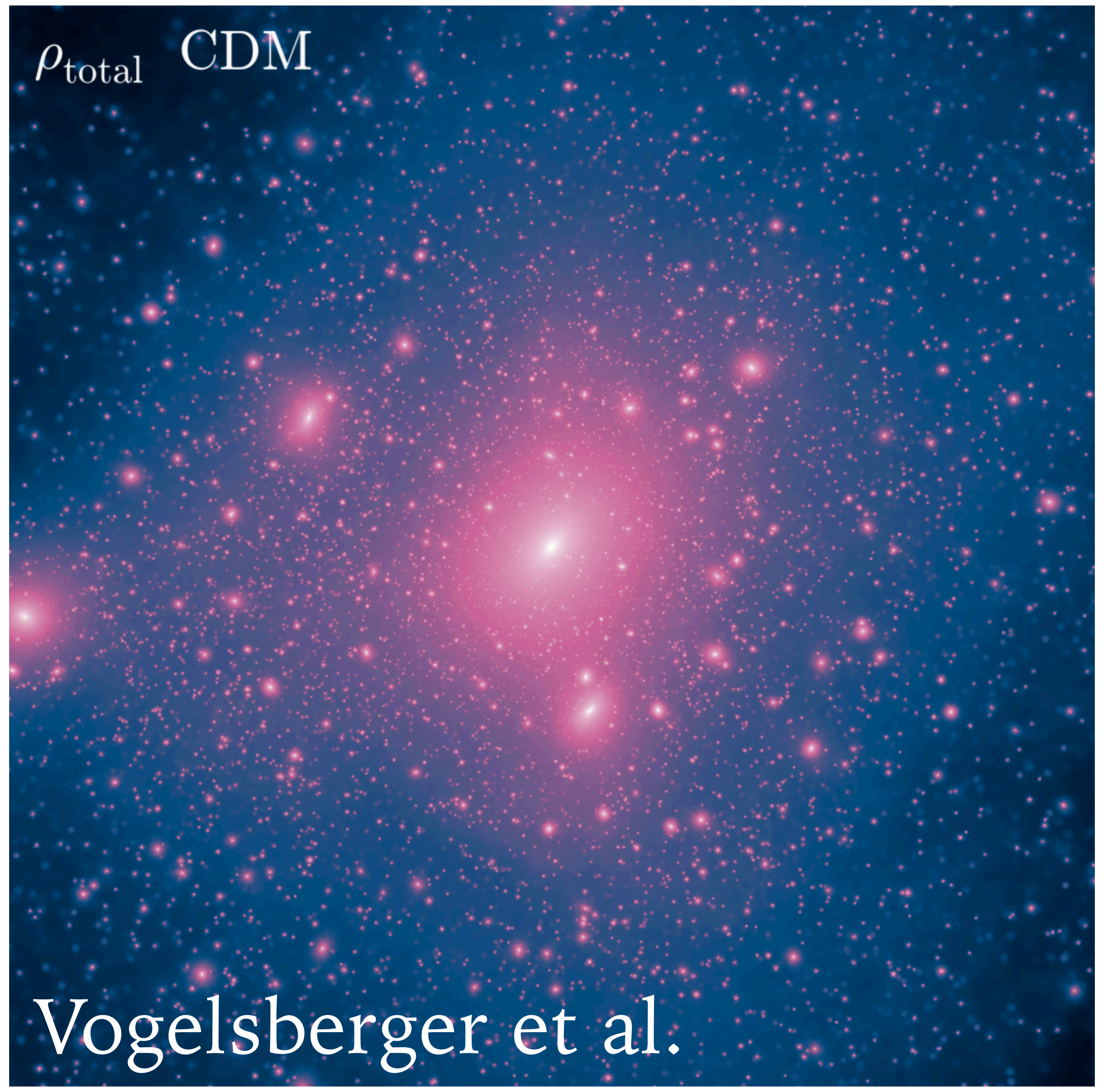
More reading: Halo Probes of Dark Matter (Snowmass Solicited White Paper)

facilitated by Keith Bechtol, Simon Birrer, Francis-Yan Cyr-Racine, **KS**

TYPE OF EFFECT WE CAN STUDY #1: IN SITU

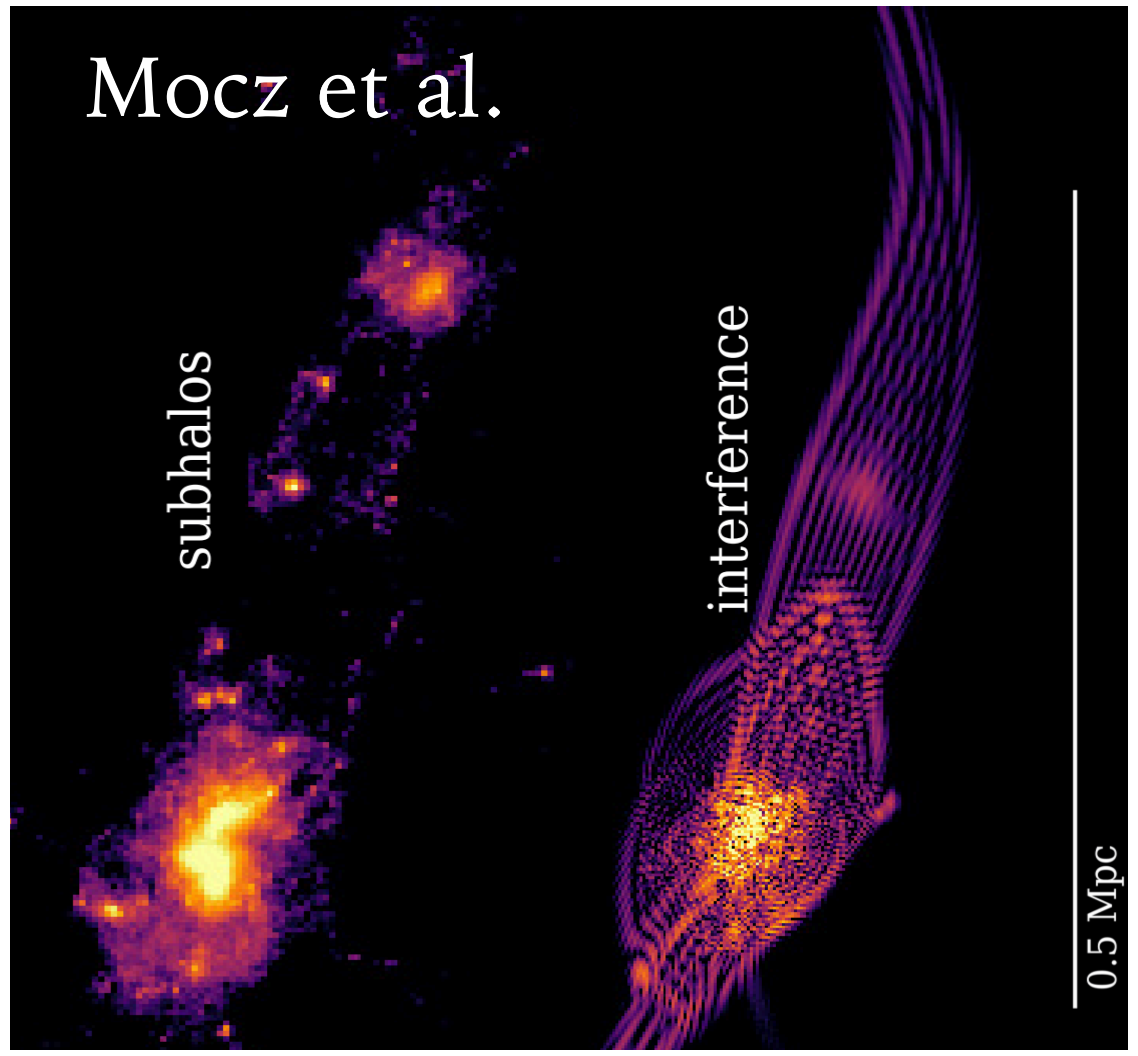
Drawing by Saniya Heeba & **KS**

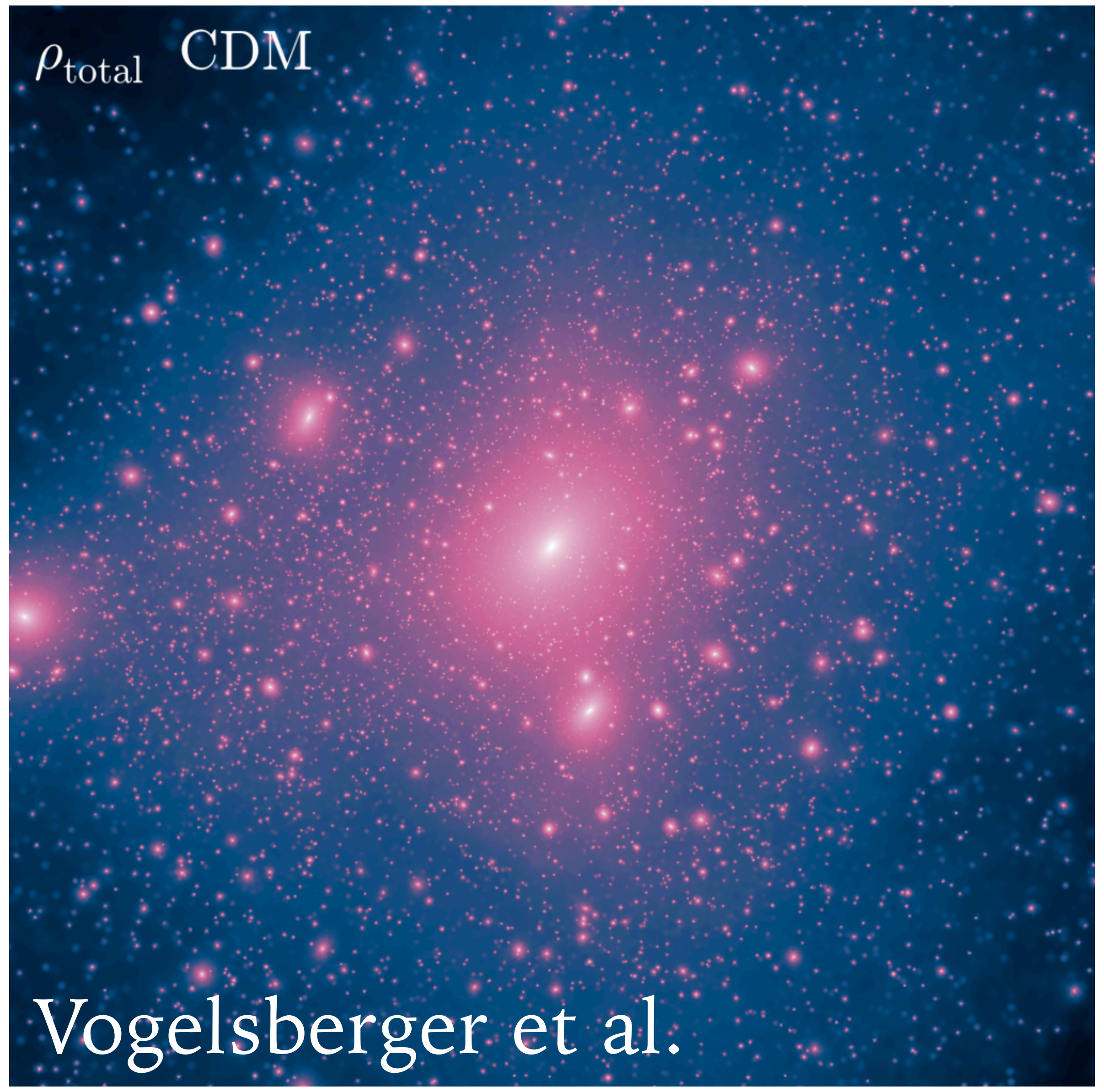
TYPE OF EFFECT WE CAN STUDY #1: IN SITU



Drawing by Saniya Heeba & **KS**

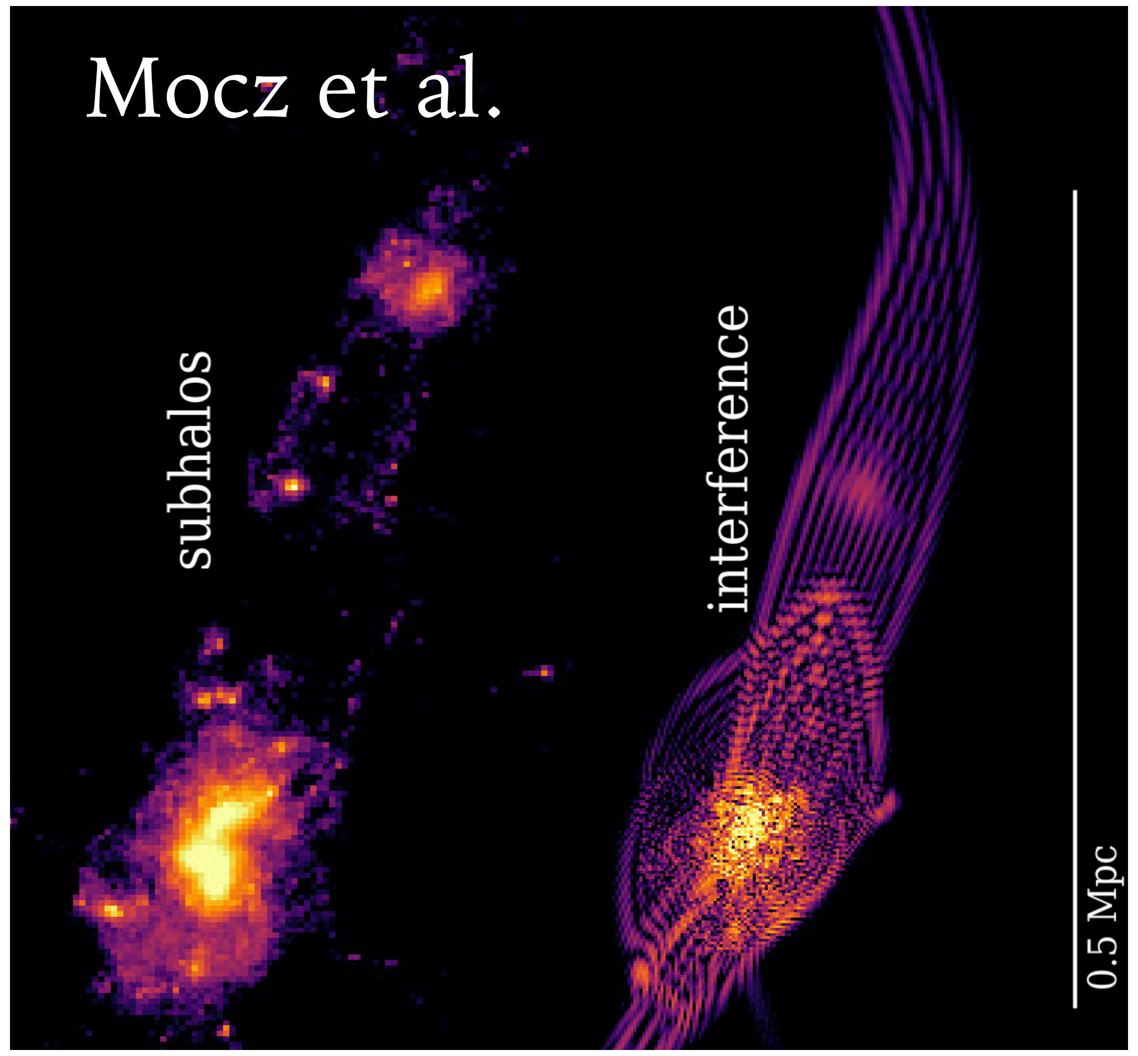
TYPE OF EFFECT WE CAN STUDY #1: IN SITU

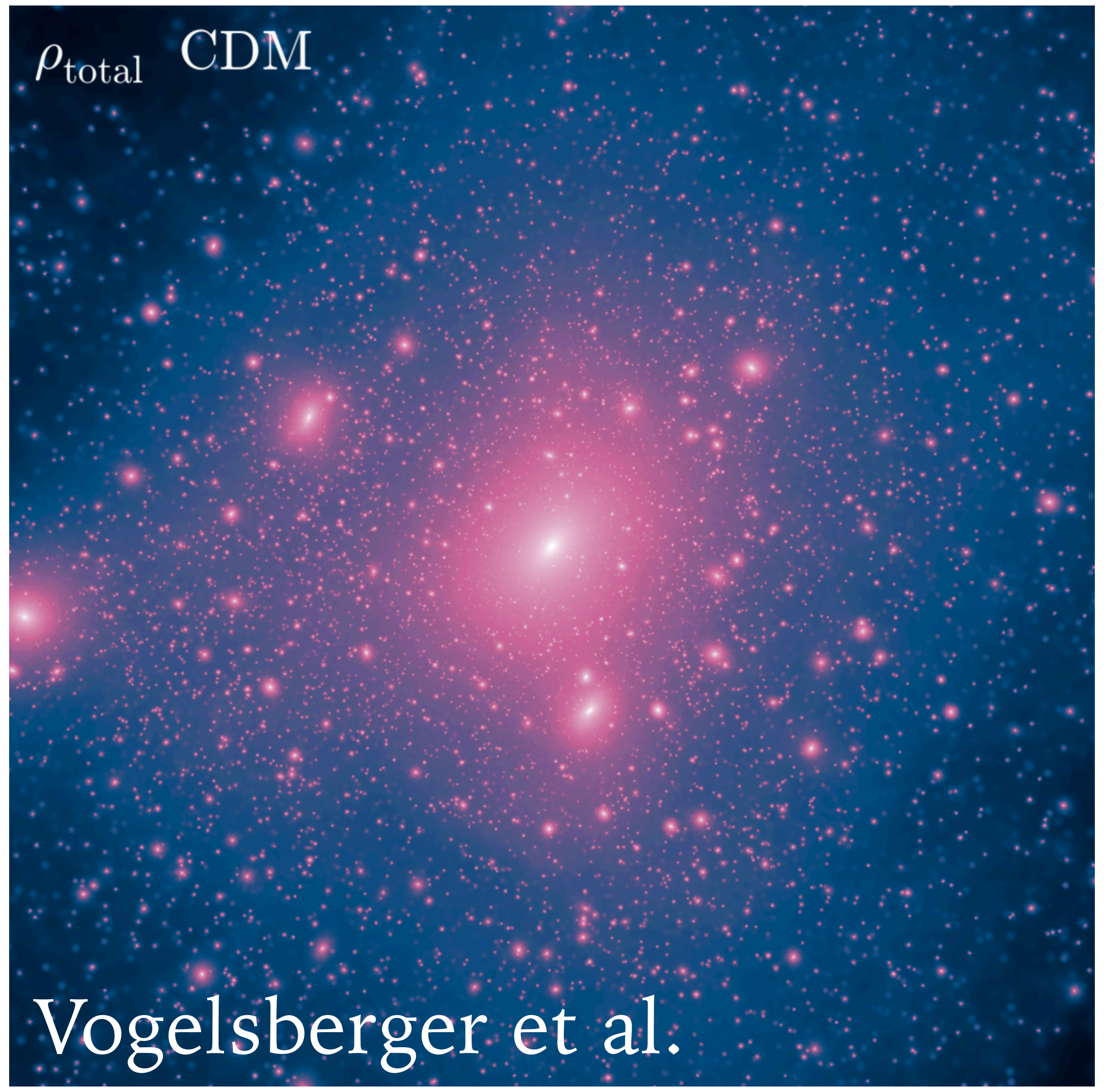


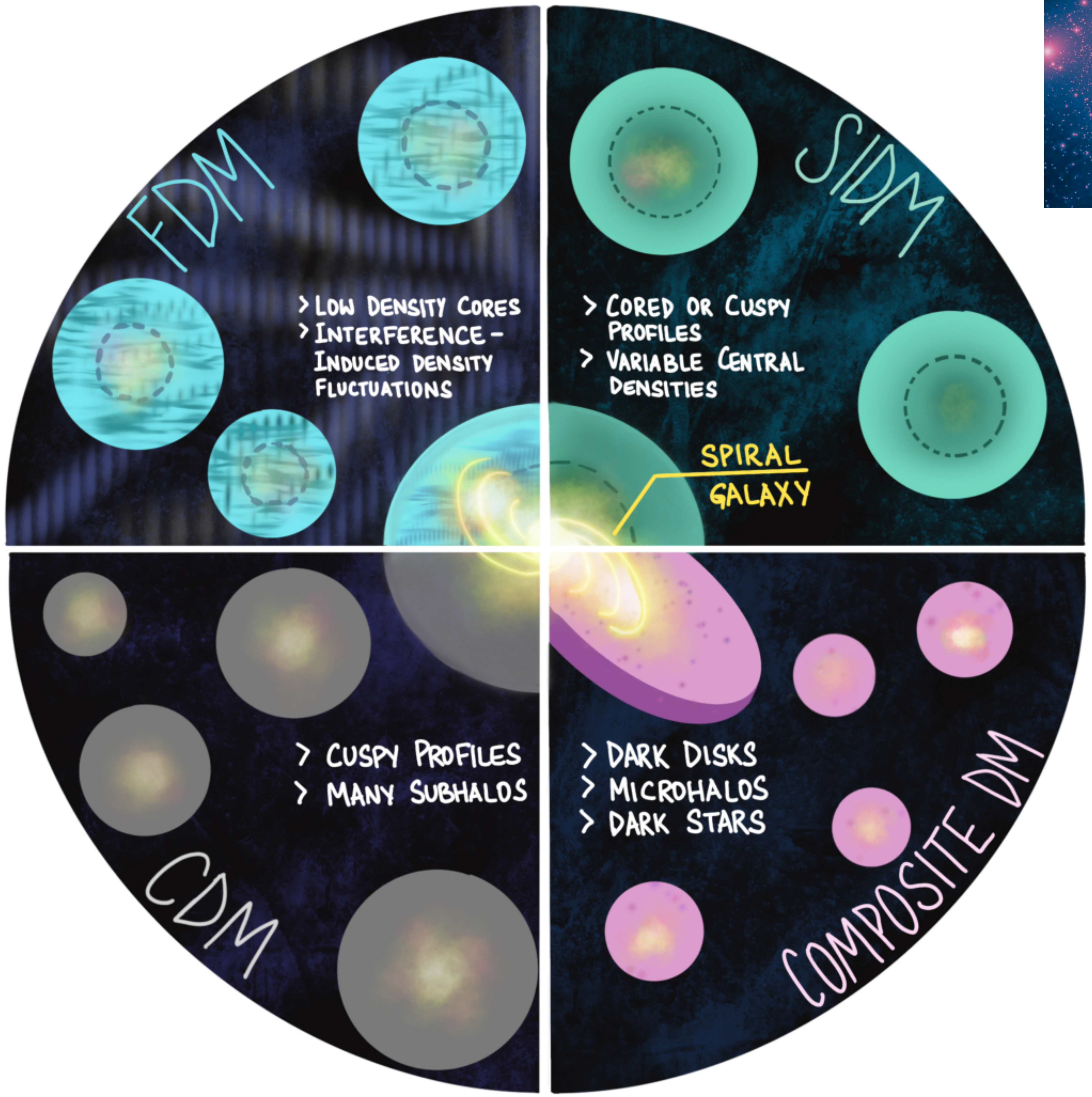


Drawing by Saniya Heeba & **KS**

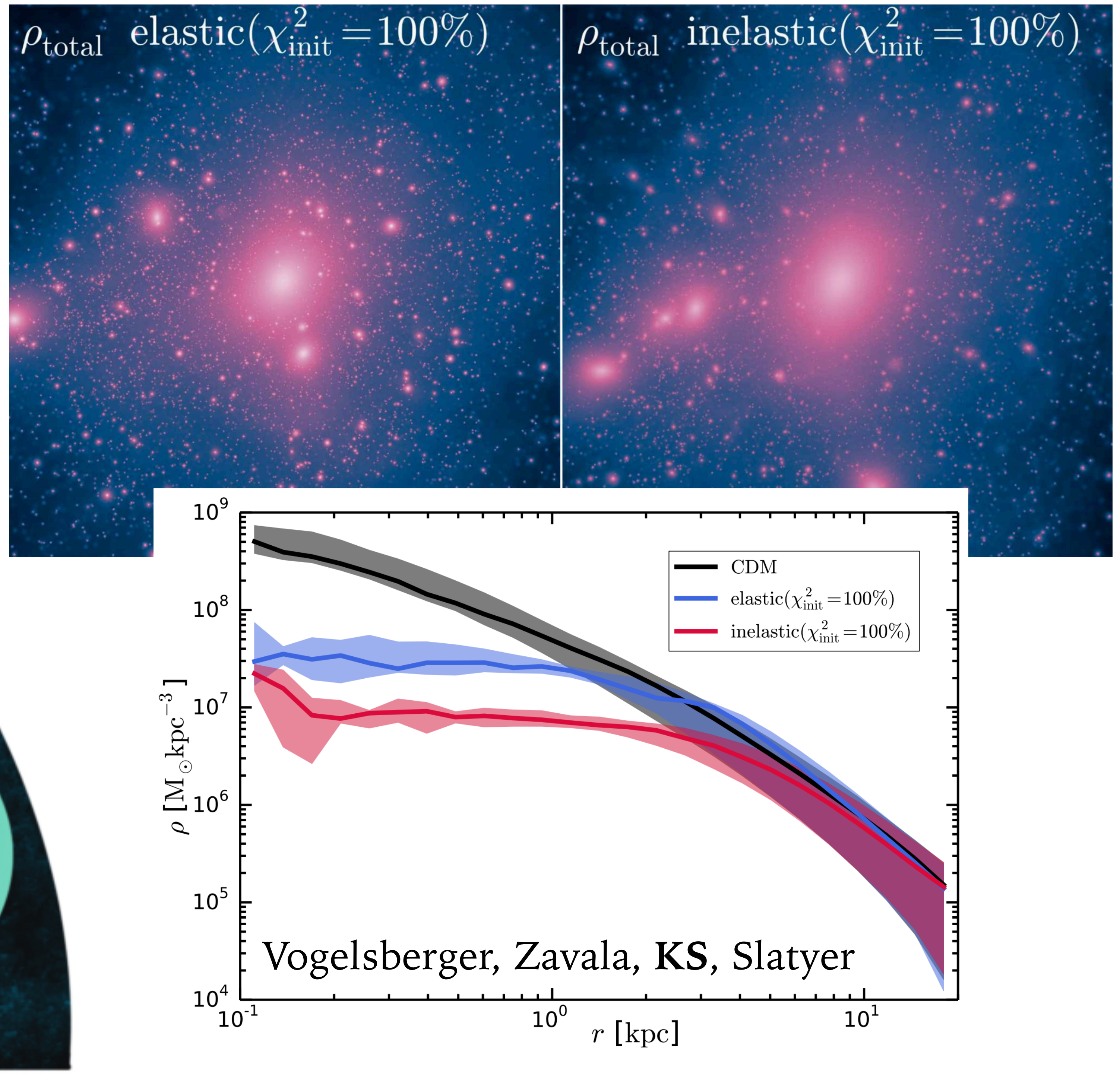
TYPE OF EFFECT WE CAN STUDY #1: IN SITU



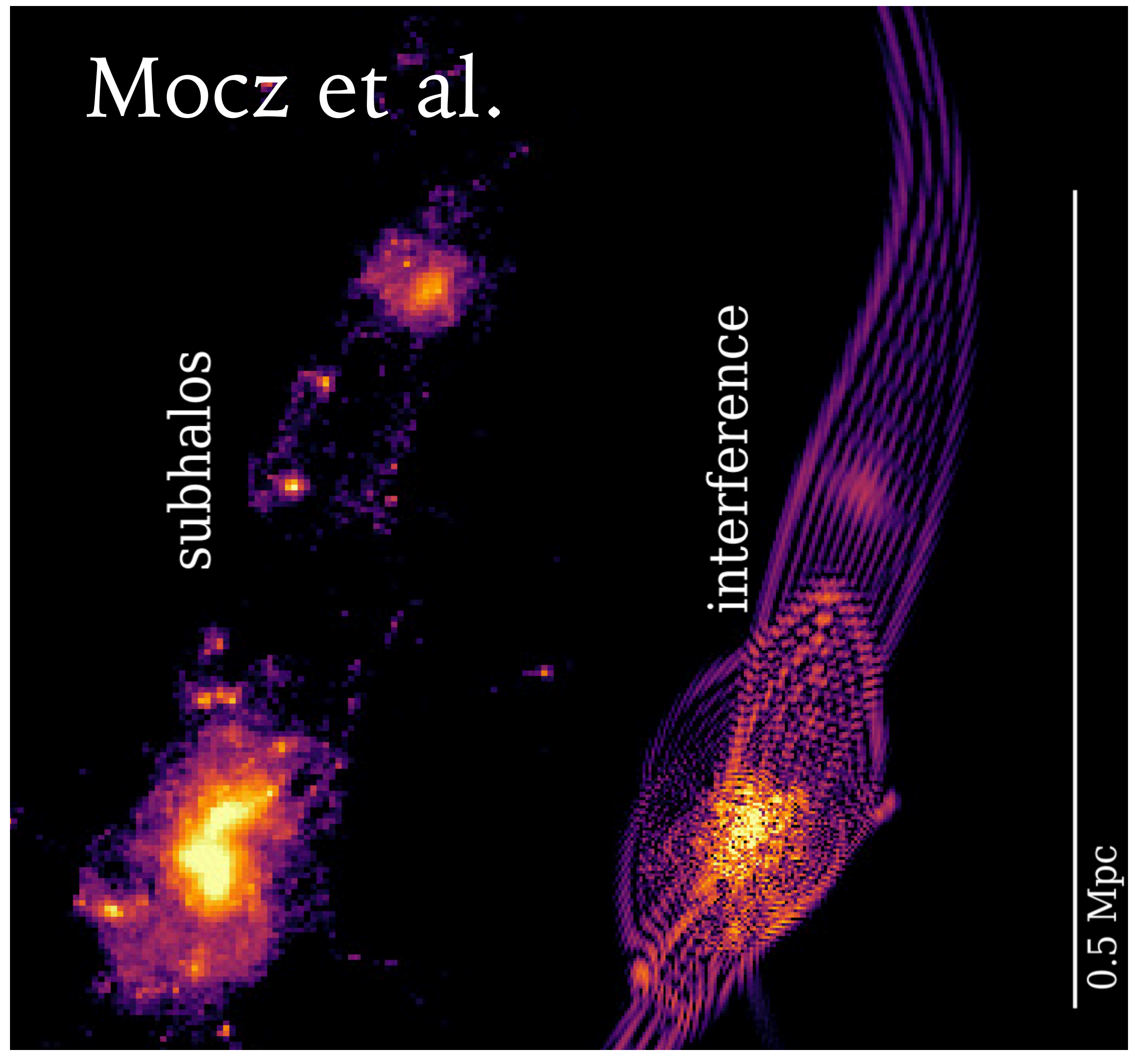


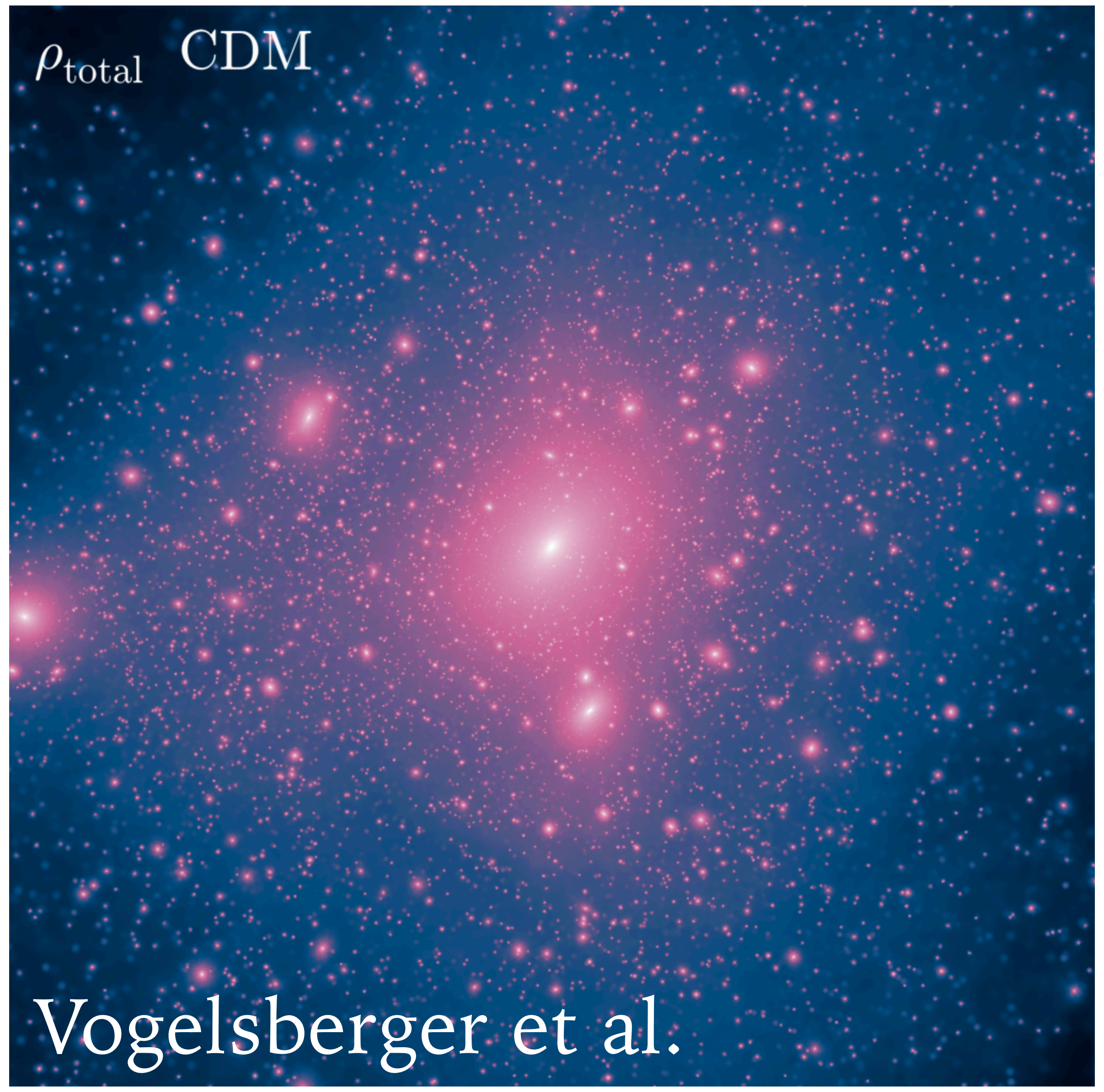


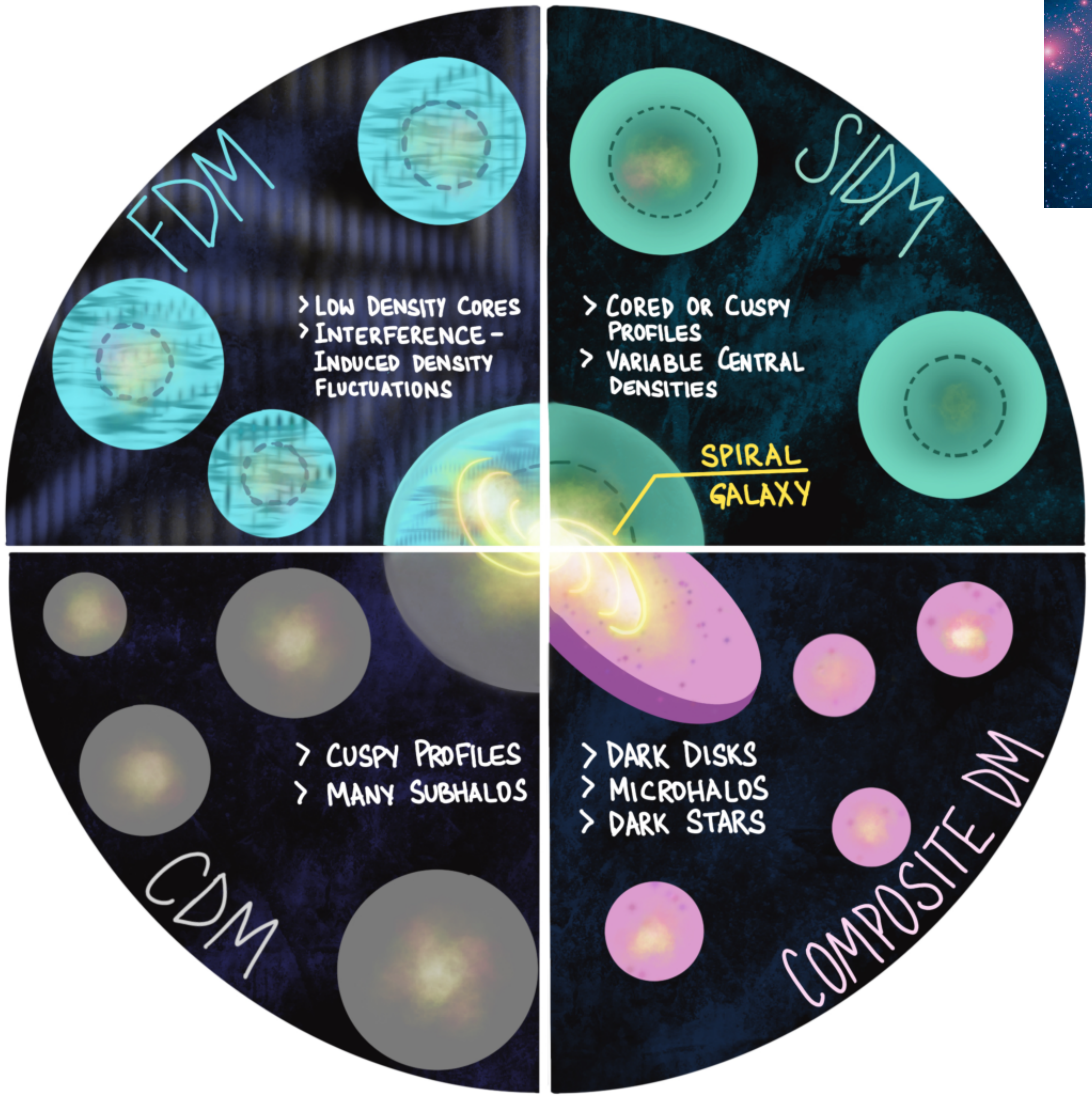
Drawing by Saniya Heeba & **KS**



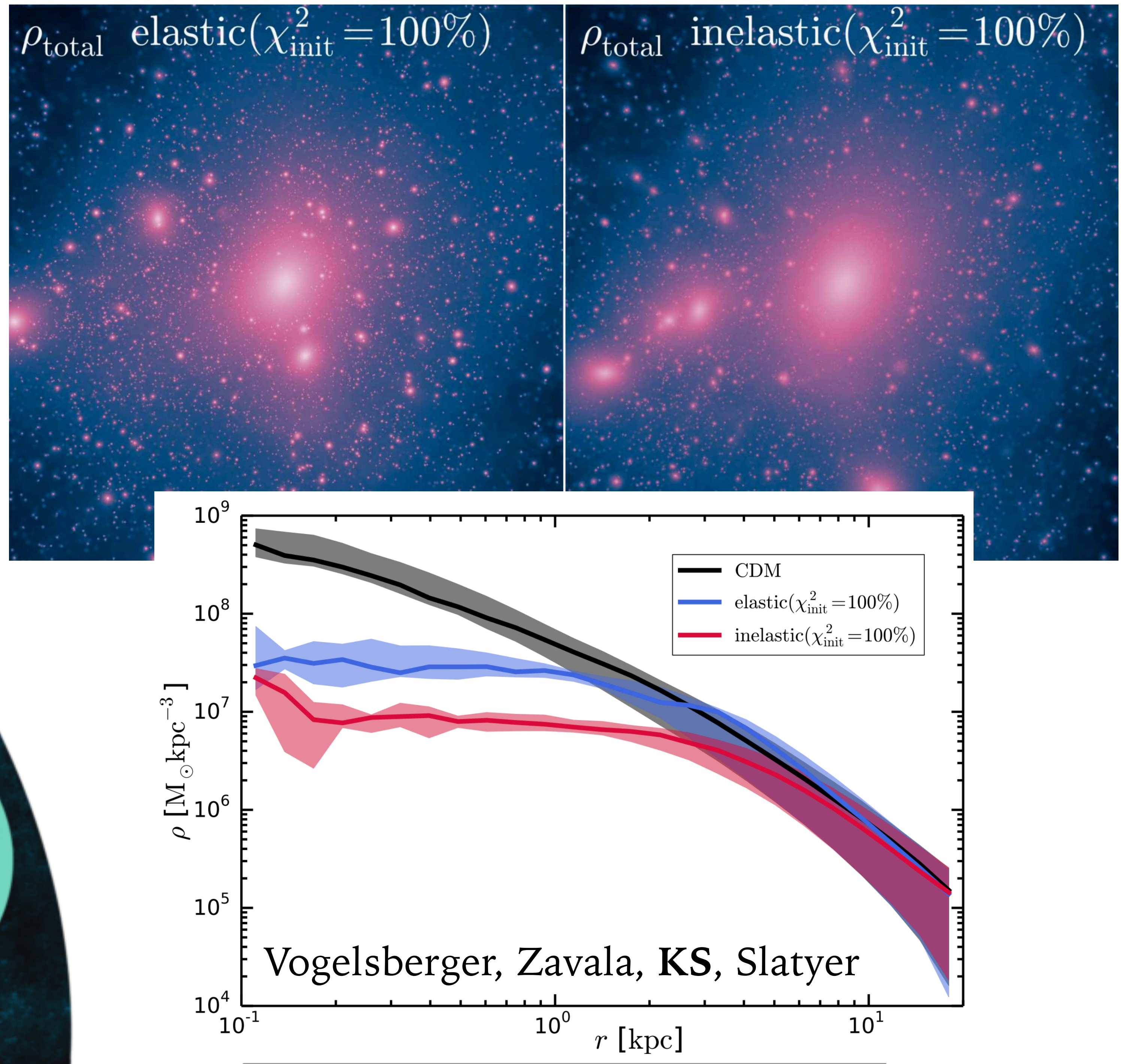
TYPE OF EFFECT WE CAN STUDY #1: IN SITU

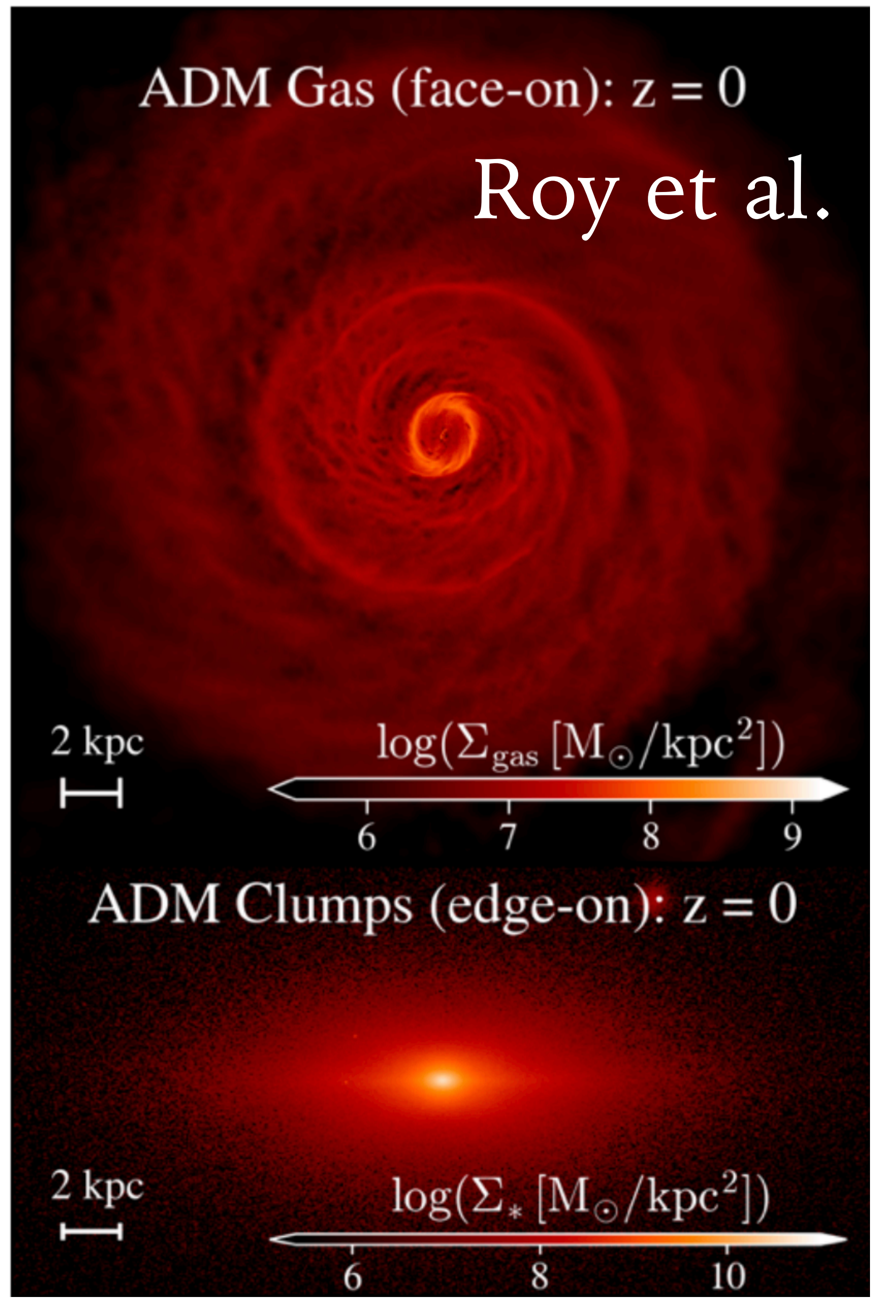




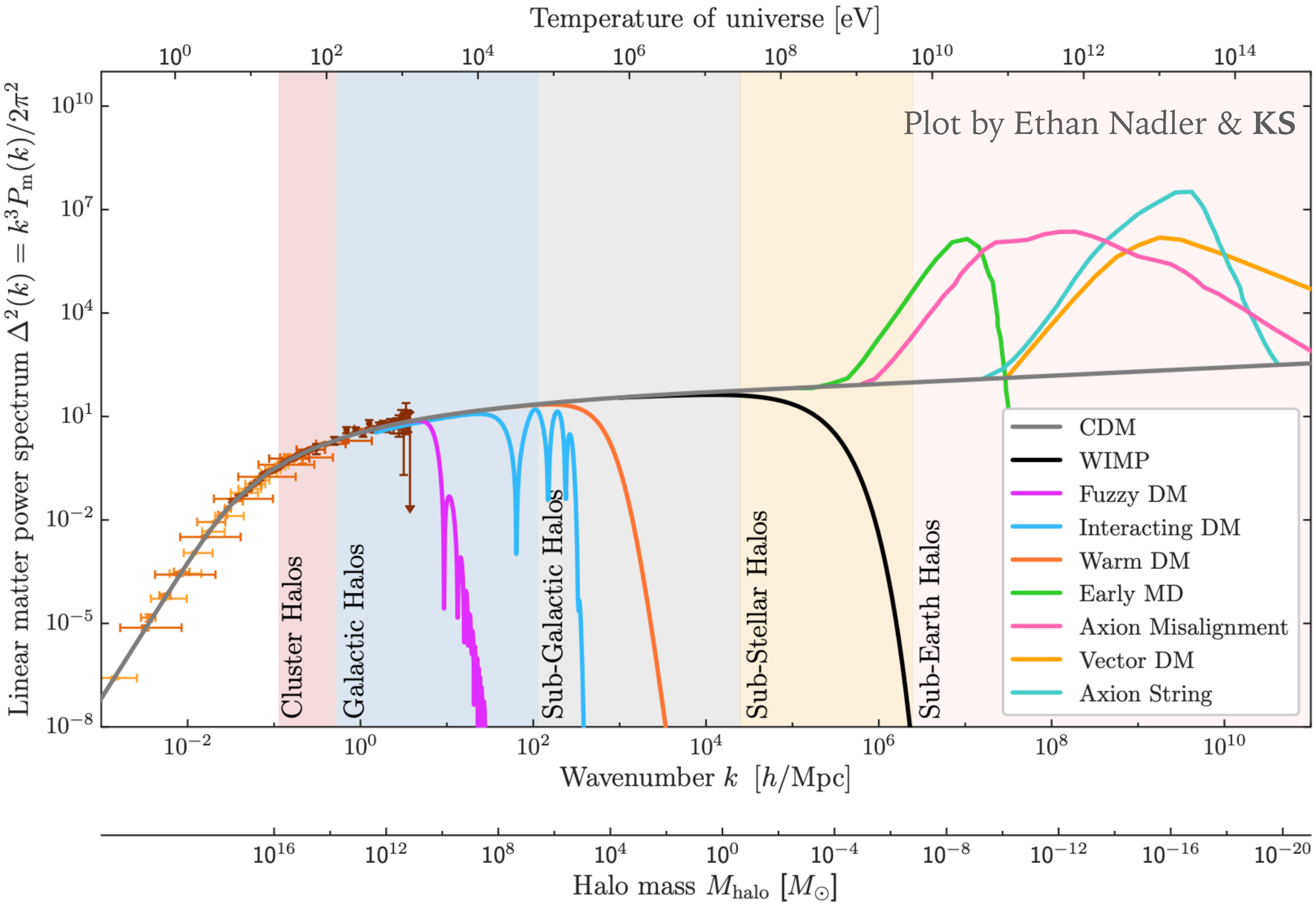


Drawing by Saniya Heeba & **KS**



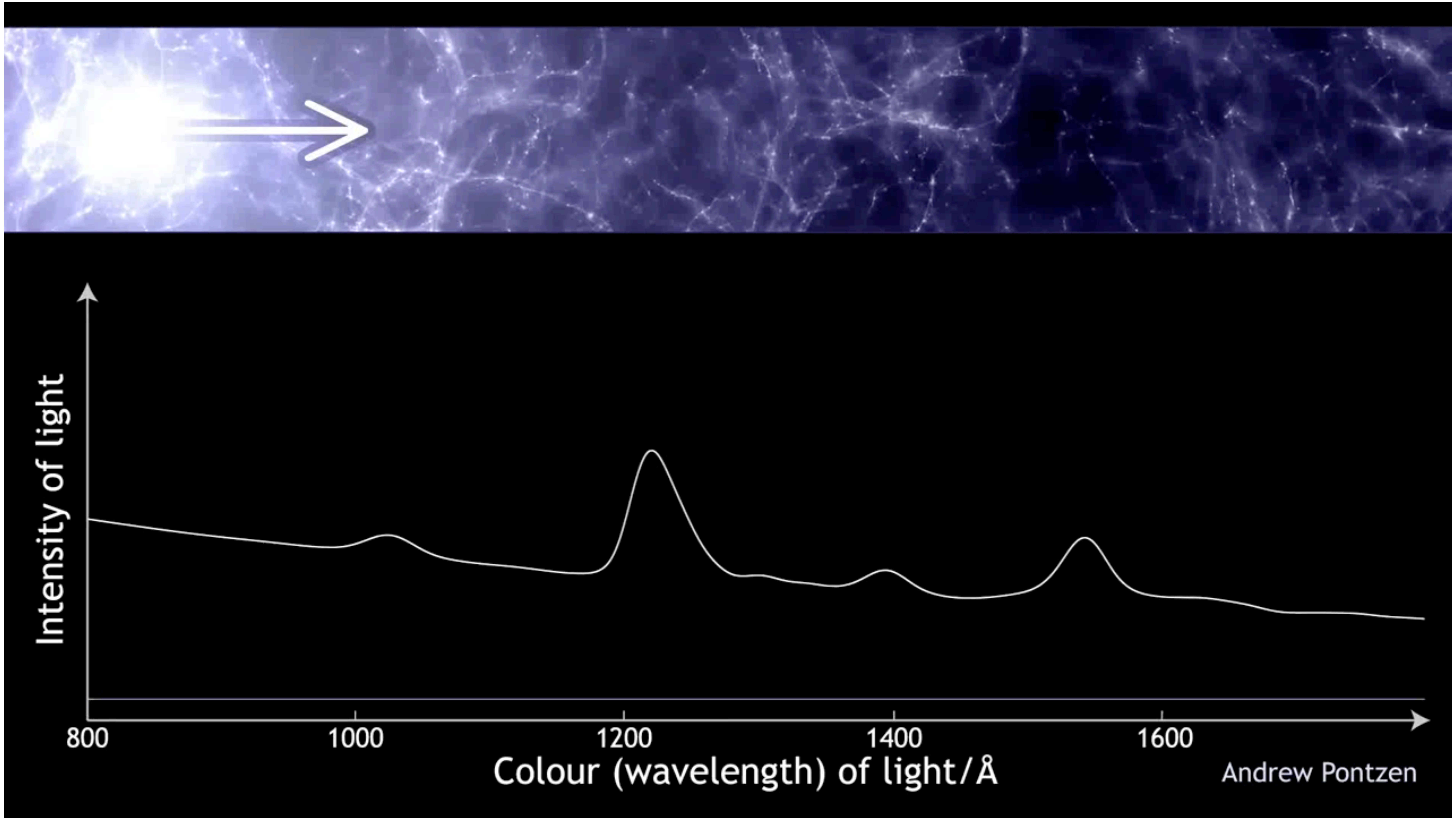


TYPE OF EFFECT WE CAN STUDY #2: AB INITIO

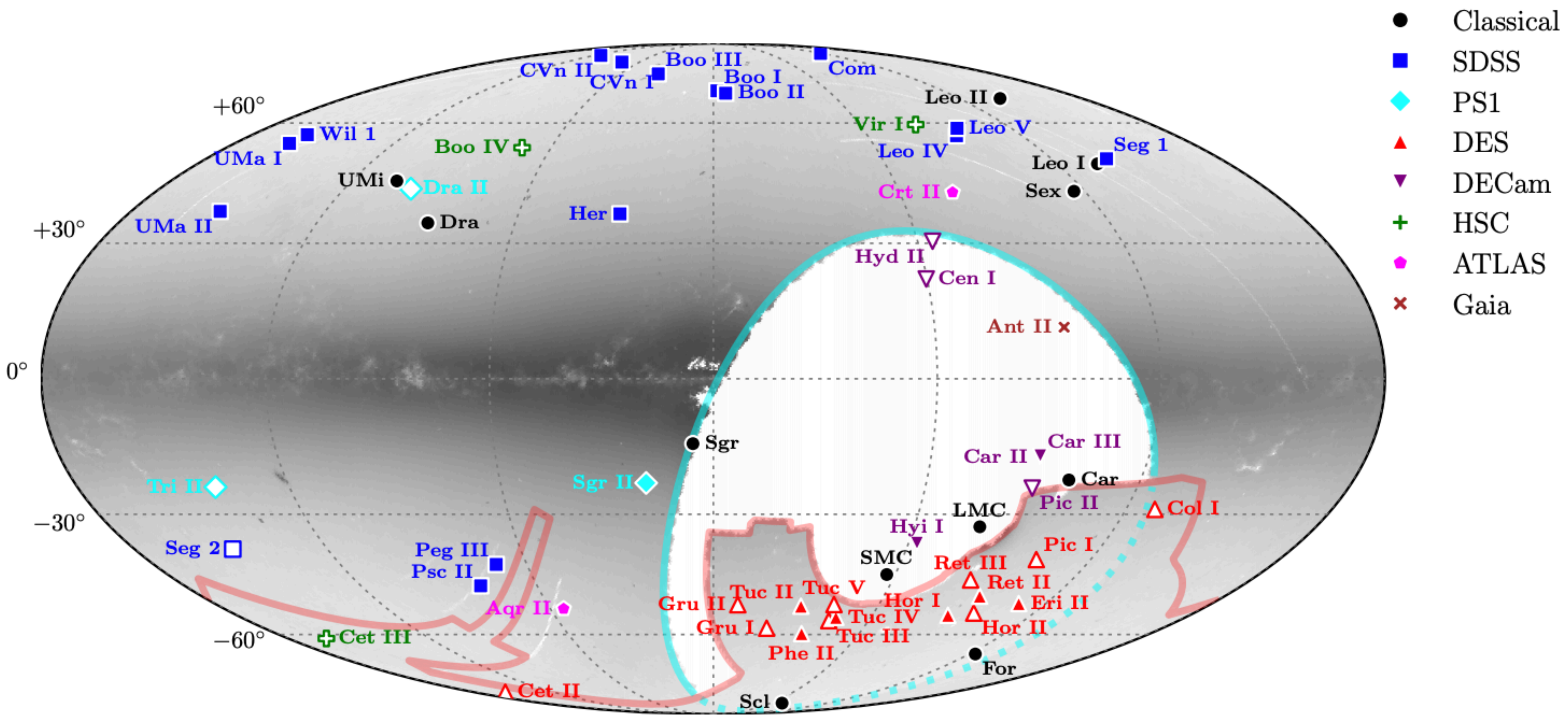


WHAT ARE SOME CURRENT TECHNIQUES FOR DETECTING STRUCTURE ON SMALLER SCALES?

PROBING STRUCTURE WITH THE LYMAN-ALPHA FOREST



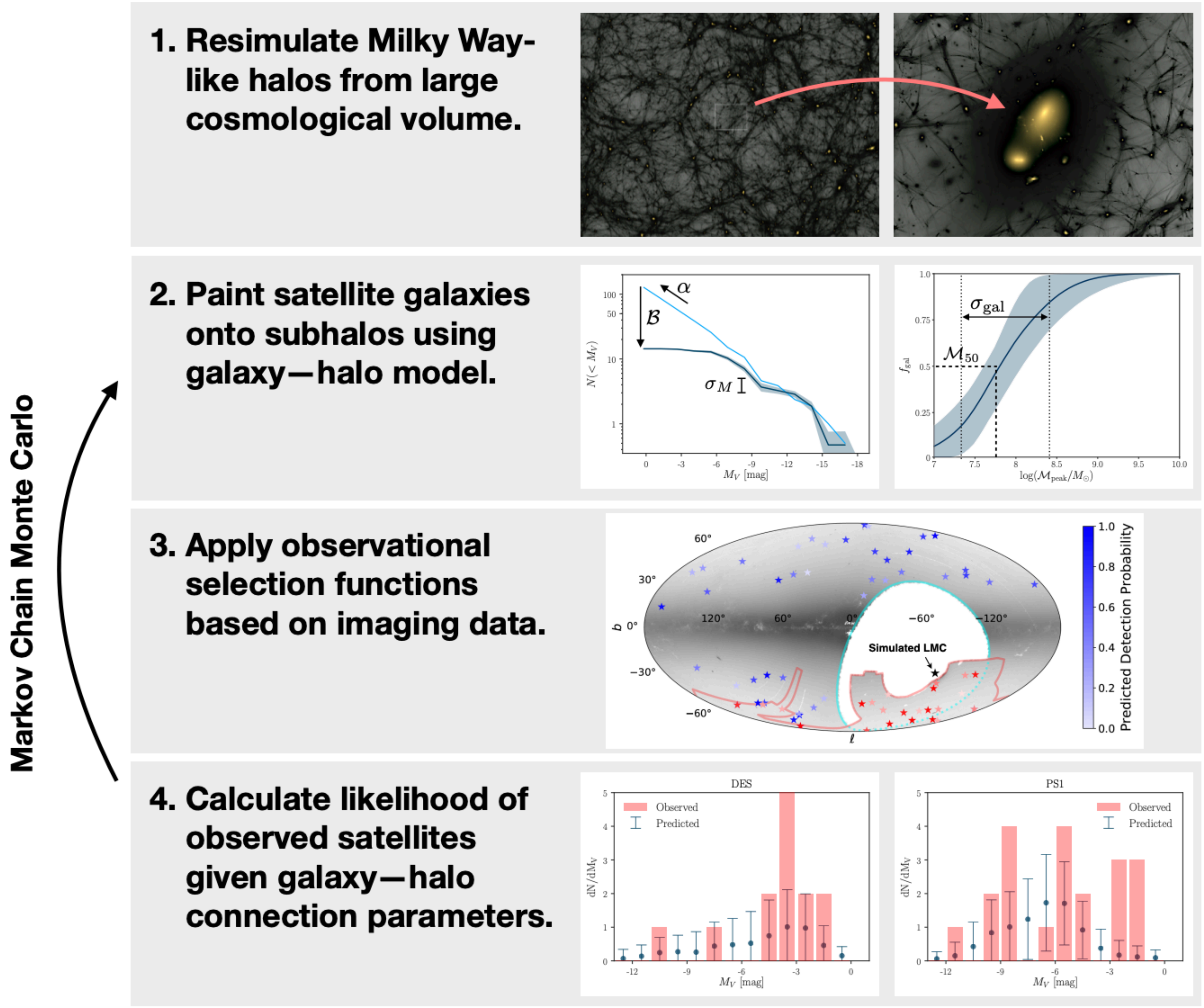
FINDING NEW DWARF GALAXIES



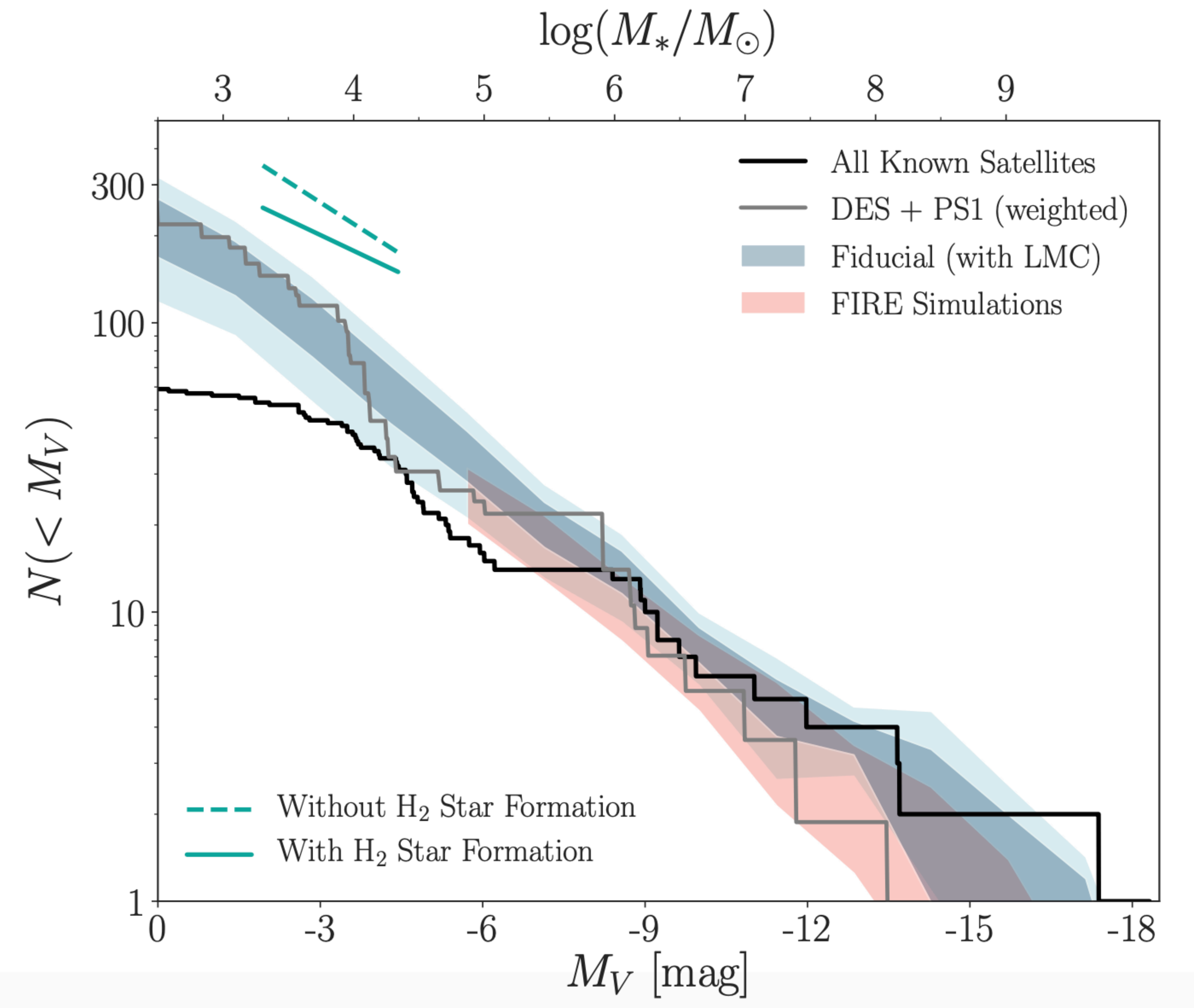
Drlica-Wagner et al. (DES collaboration, 2019)

UNDERSTANDING GALAXY-HALO CONNECTION EMPIRICALLY

Nadler et al. (DES Collaboration 2019)



UNDERSTANDING GALAXY-HALO CONNECTION EMPIRICALLY

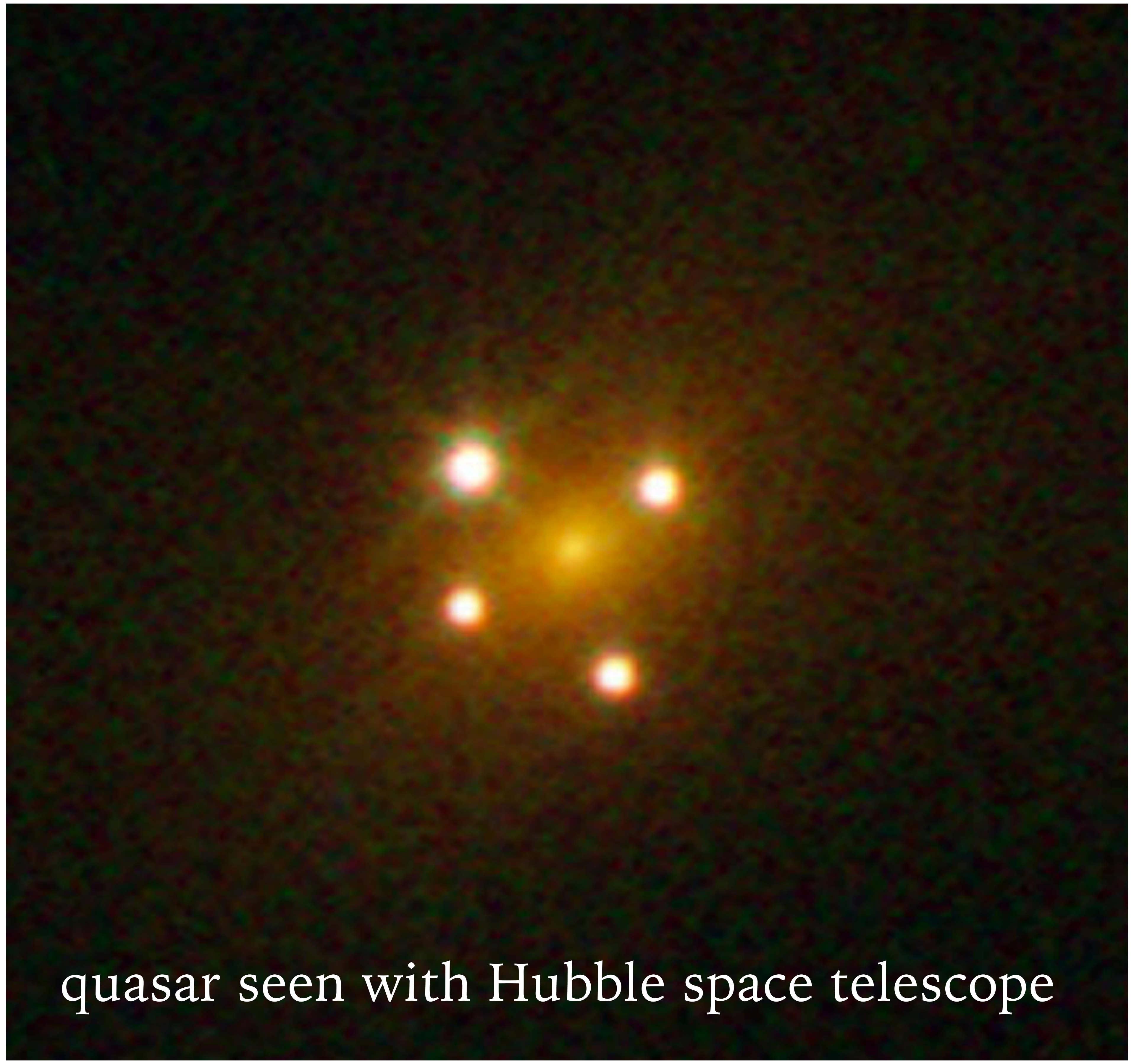


The presence of low-mass subhalos (after accounting for selection effects) is consistent with CDM

Nadler et al. (DES Collaboration 2019,2020)

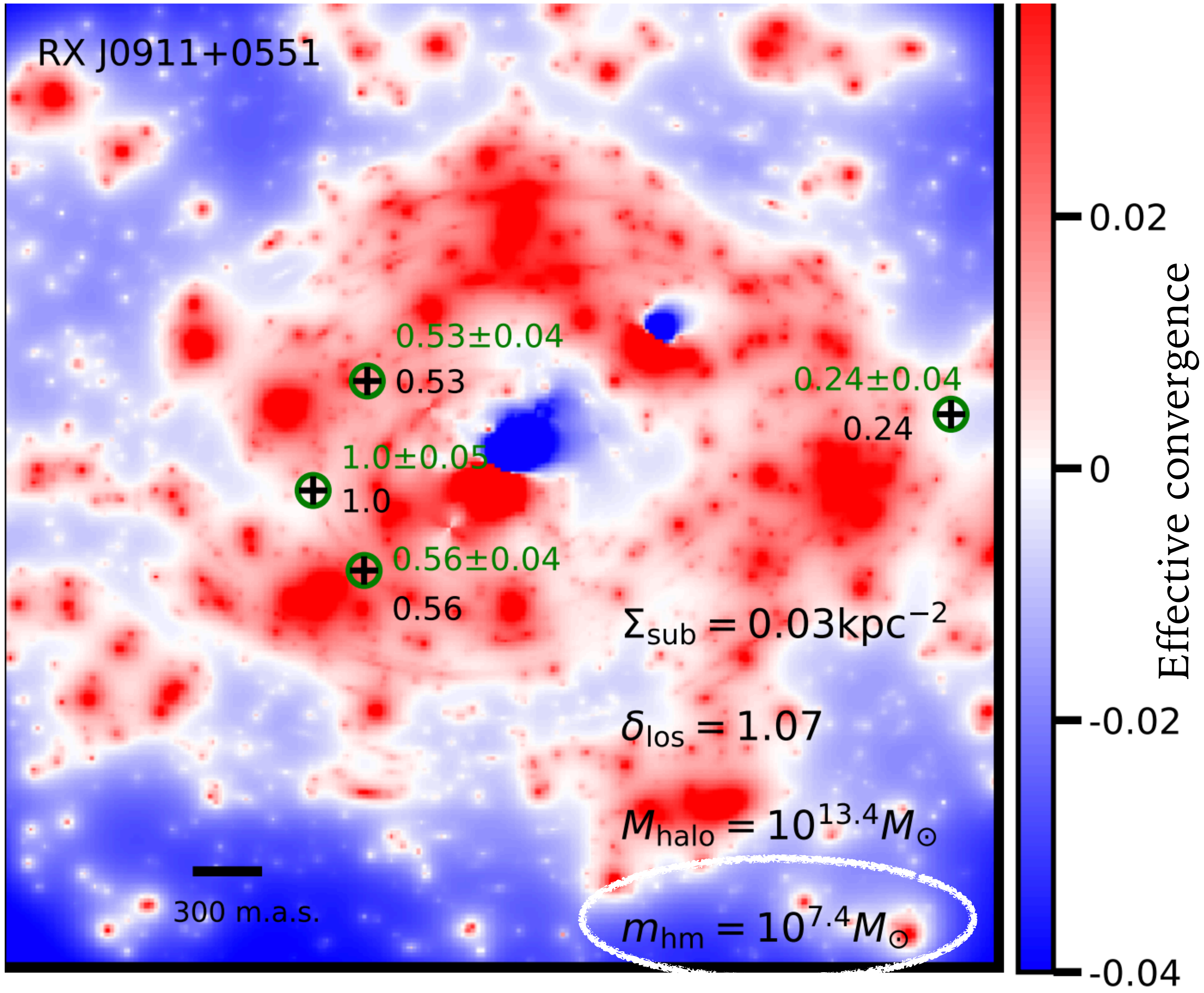
SUBSTRUCTURE CAN BE PROBED WITH GRAVITATIONAL LENSING

- Gravitationally lensed quasars can appear as four images surrounding lens galaxy
- Locations and relative fluxes of images are sensitive to substructure of lens galaxy (second derivatives of lensing potential)



quasar seen with Hubble space telescope

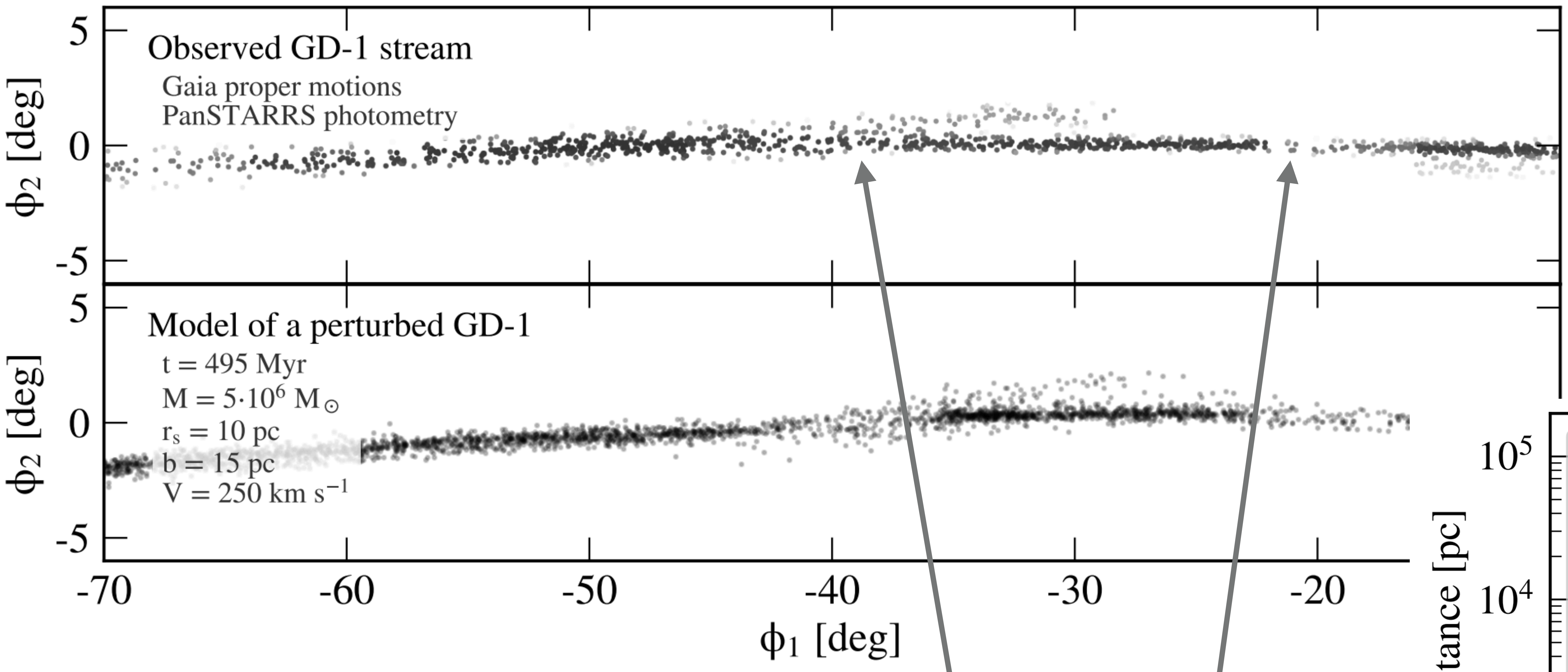
EFFECTIVE CONVERGENCE MAP (HIGH-RANKING REALIZATION)



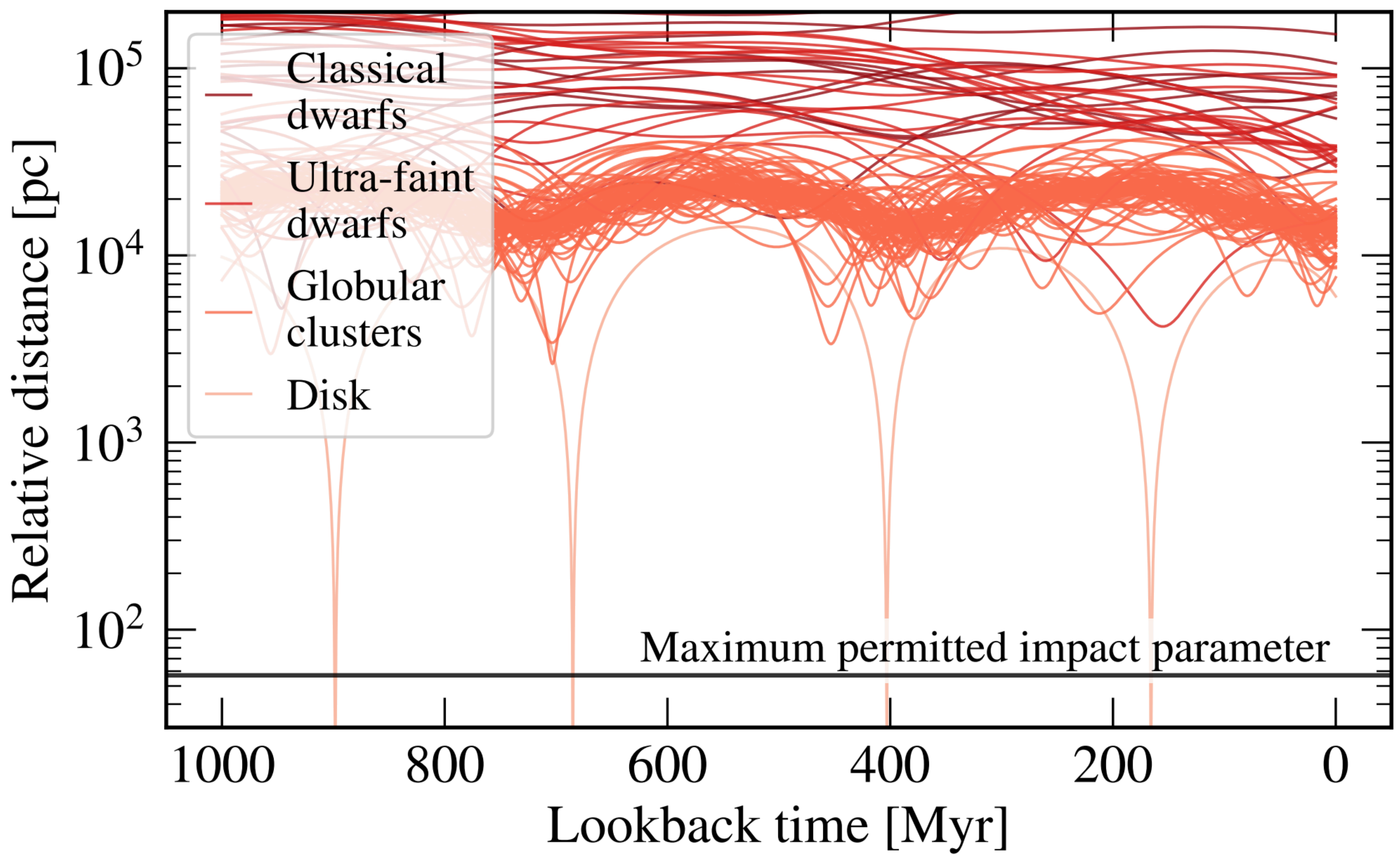
Gilman et al. (2019)

STELLAR STREAMS (~100 KNOWN IN MILKY WAY)

GAIA HAS HELPED US "CLEAN" STREAMS, FUTURE SPECTROSCOPY WITH VIA

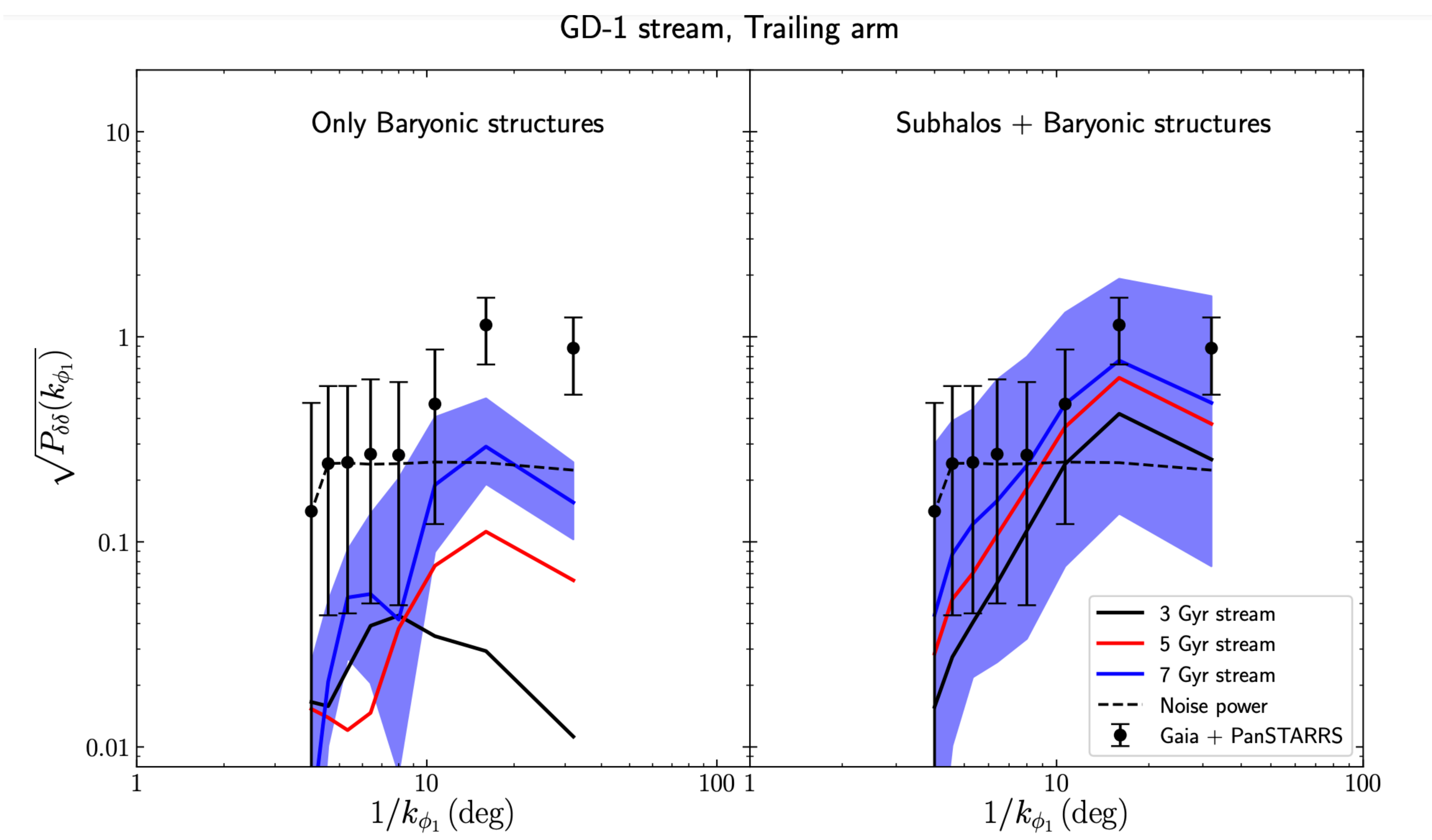


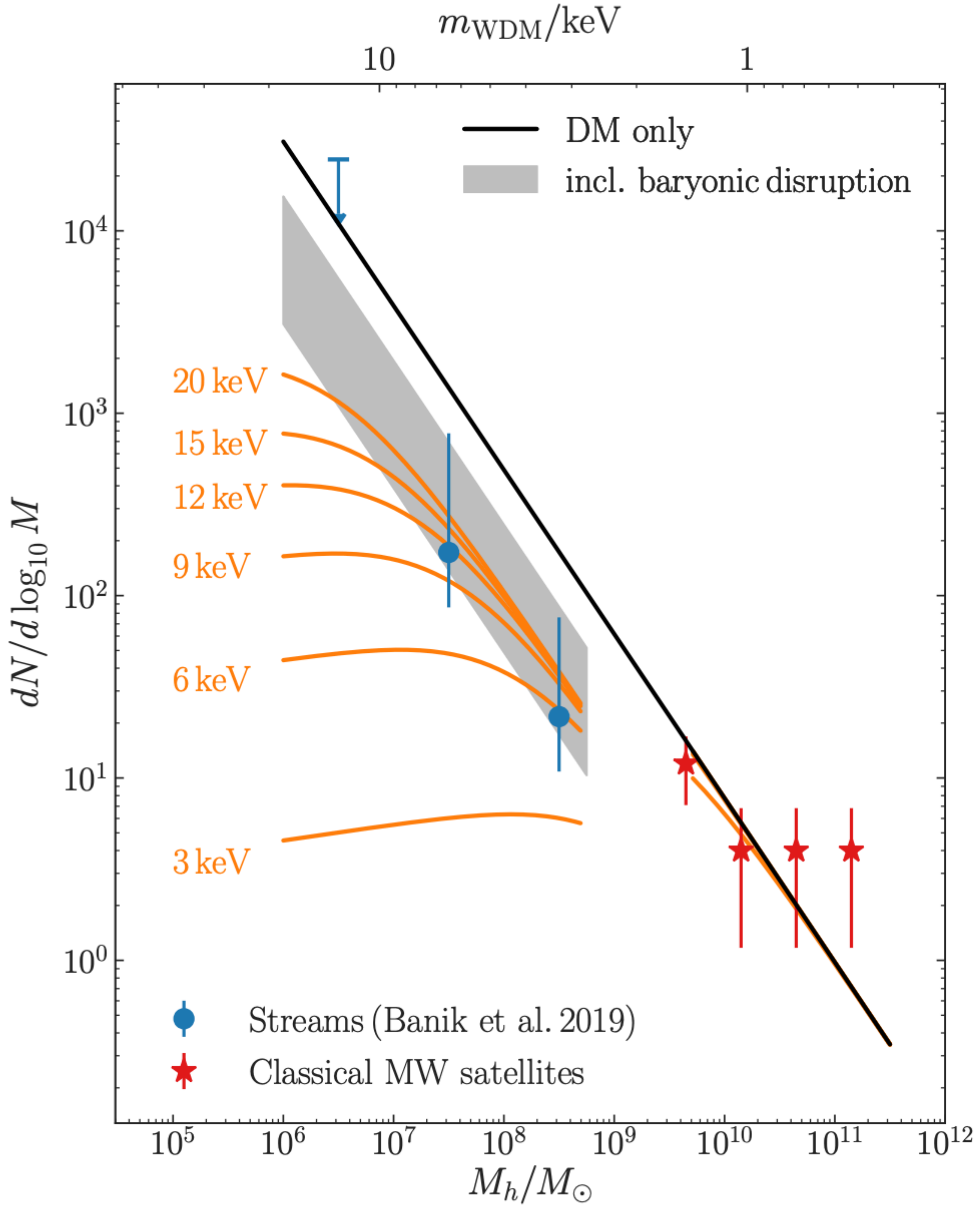
Features in stream imply a perturber that probably isn't luminous



Bonaca, Hogg, Price-Whelan, Conroy (2018)

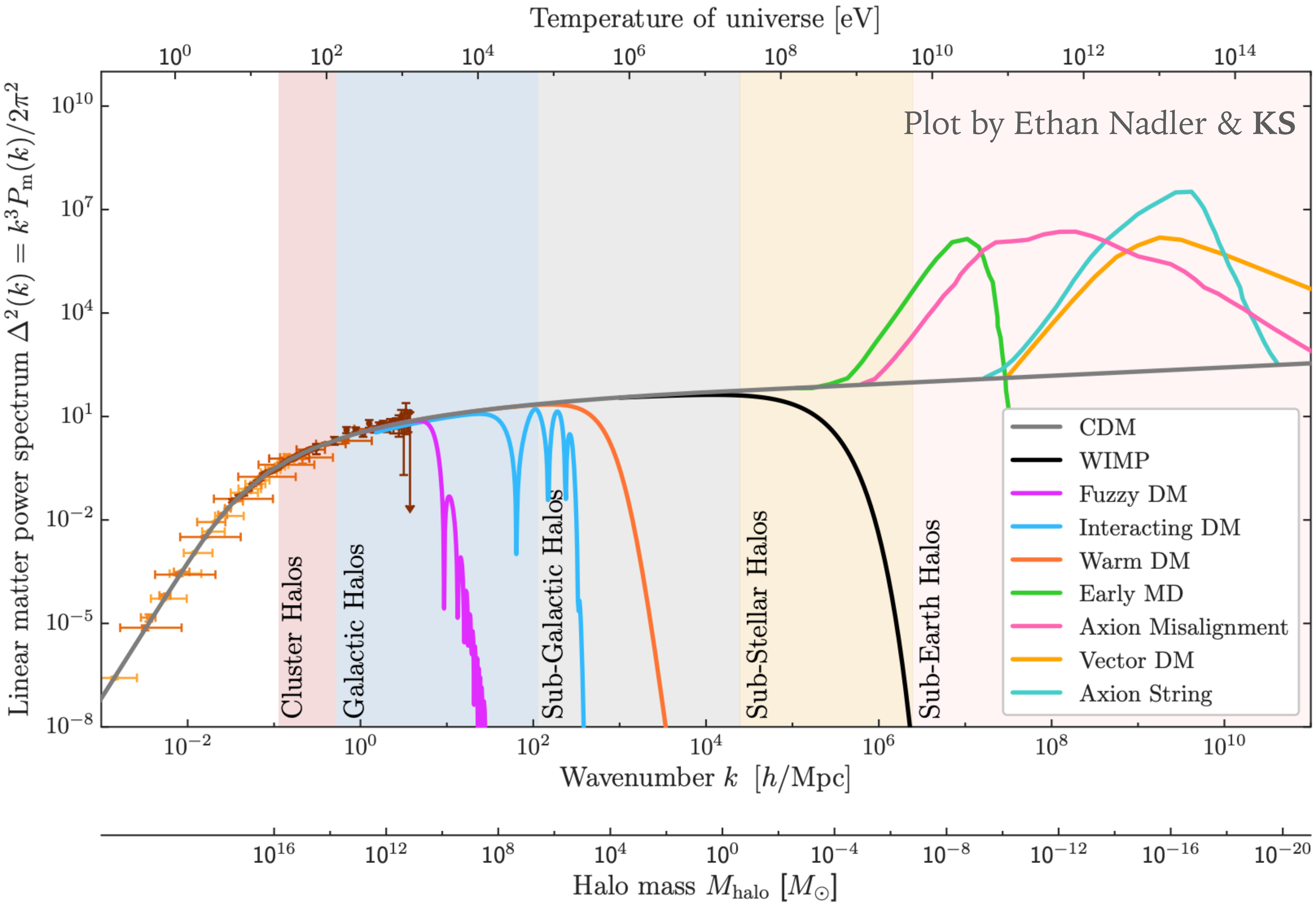
LOOKING AT POWER SPECTRUM RATHER THAN INDIVIDUAL FEATURES



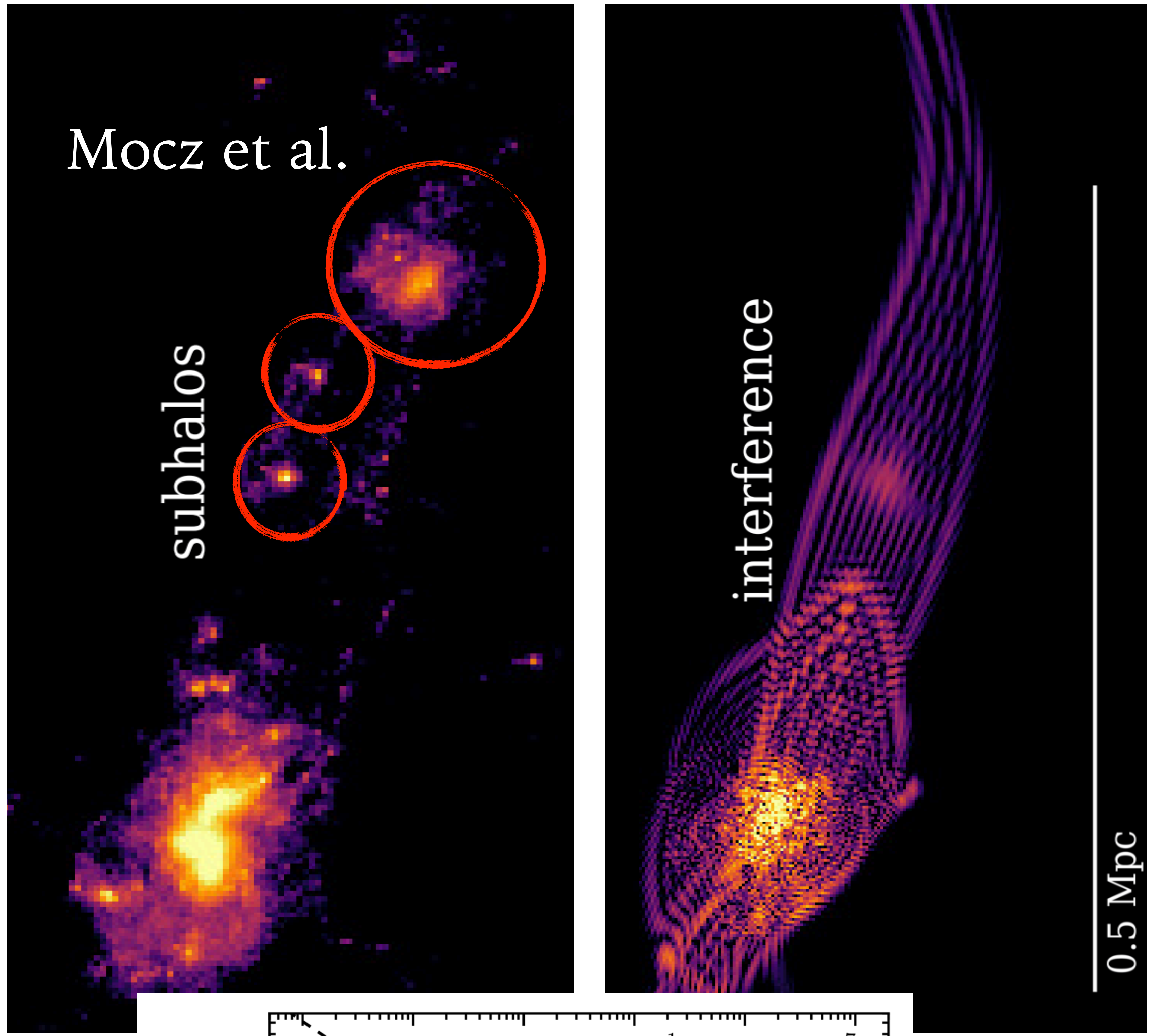


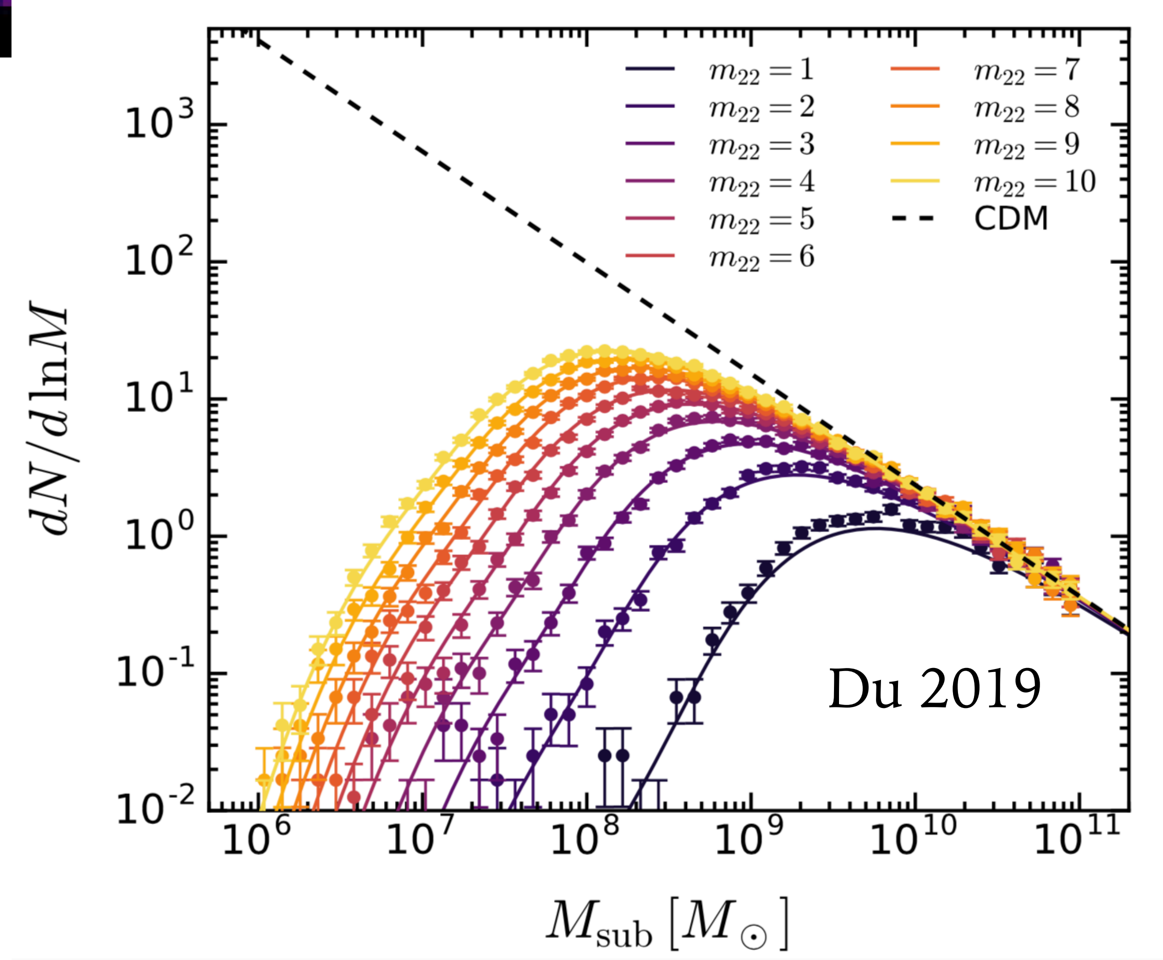
Banik, Bovy, Bertone, Erkal, deBoer (2019)

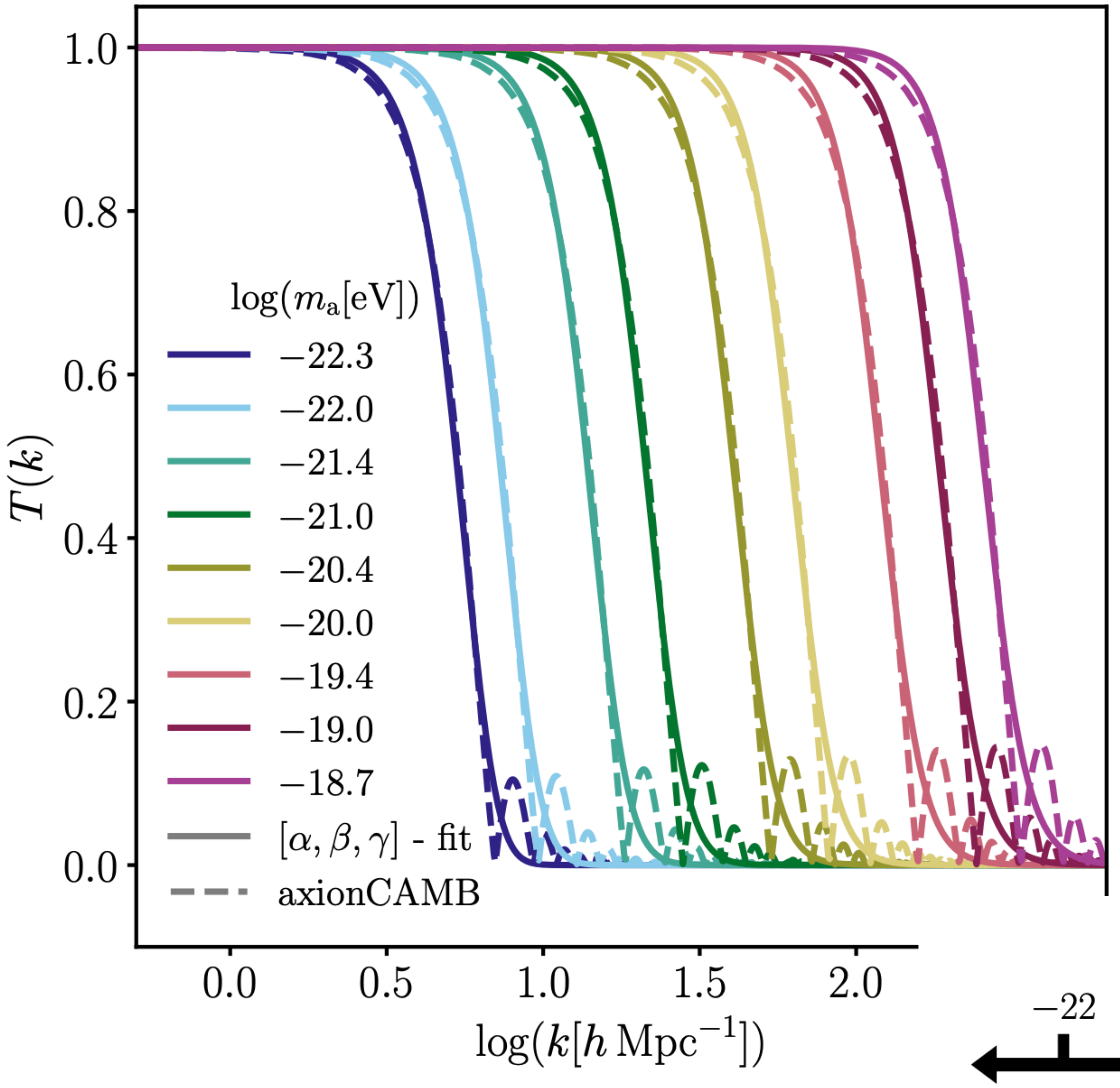
WHAT KINDS OF BSM PHYSICS CAN WE TEST WITH THIS?

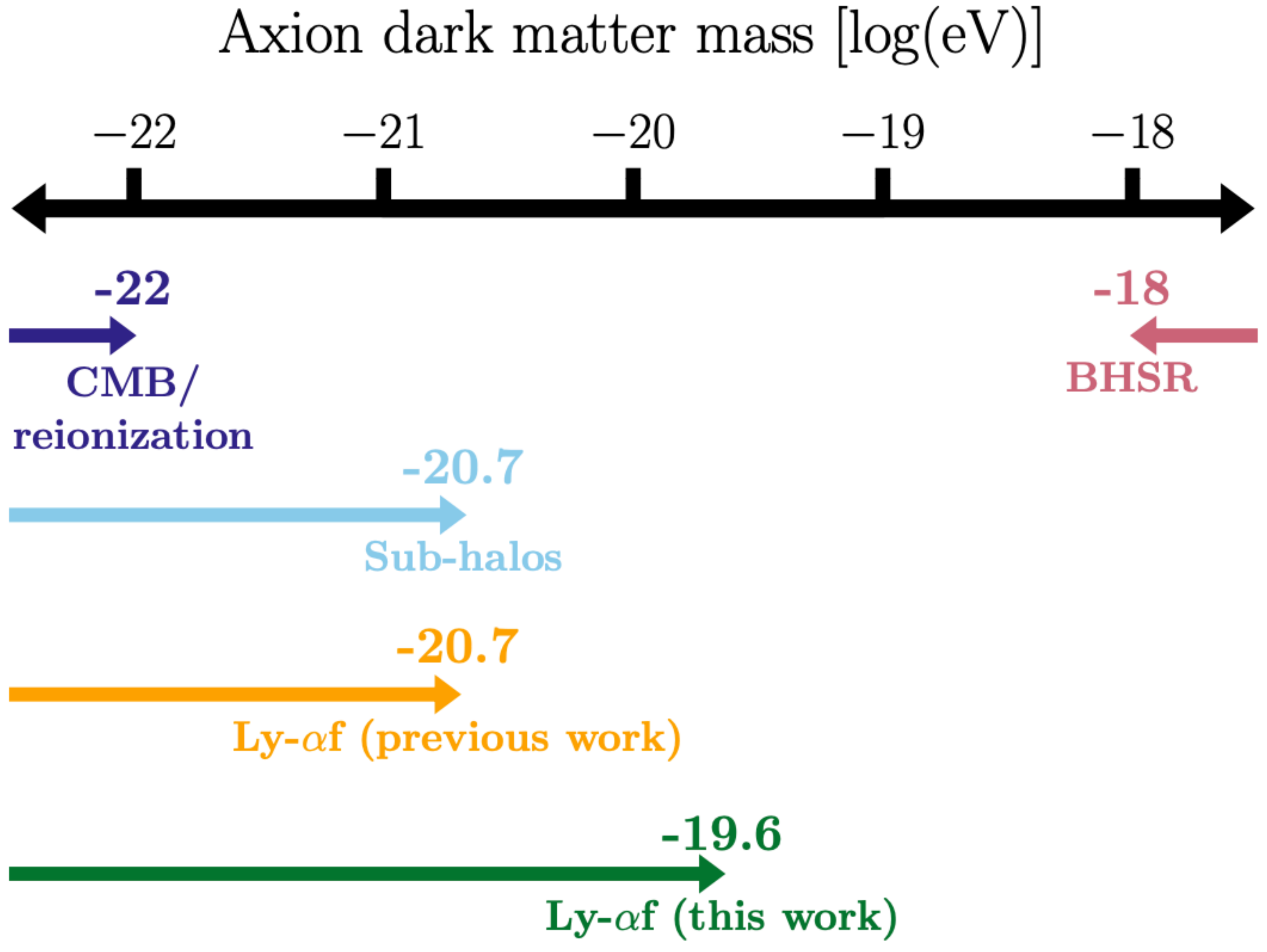


FUZZY DARK MATTER

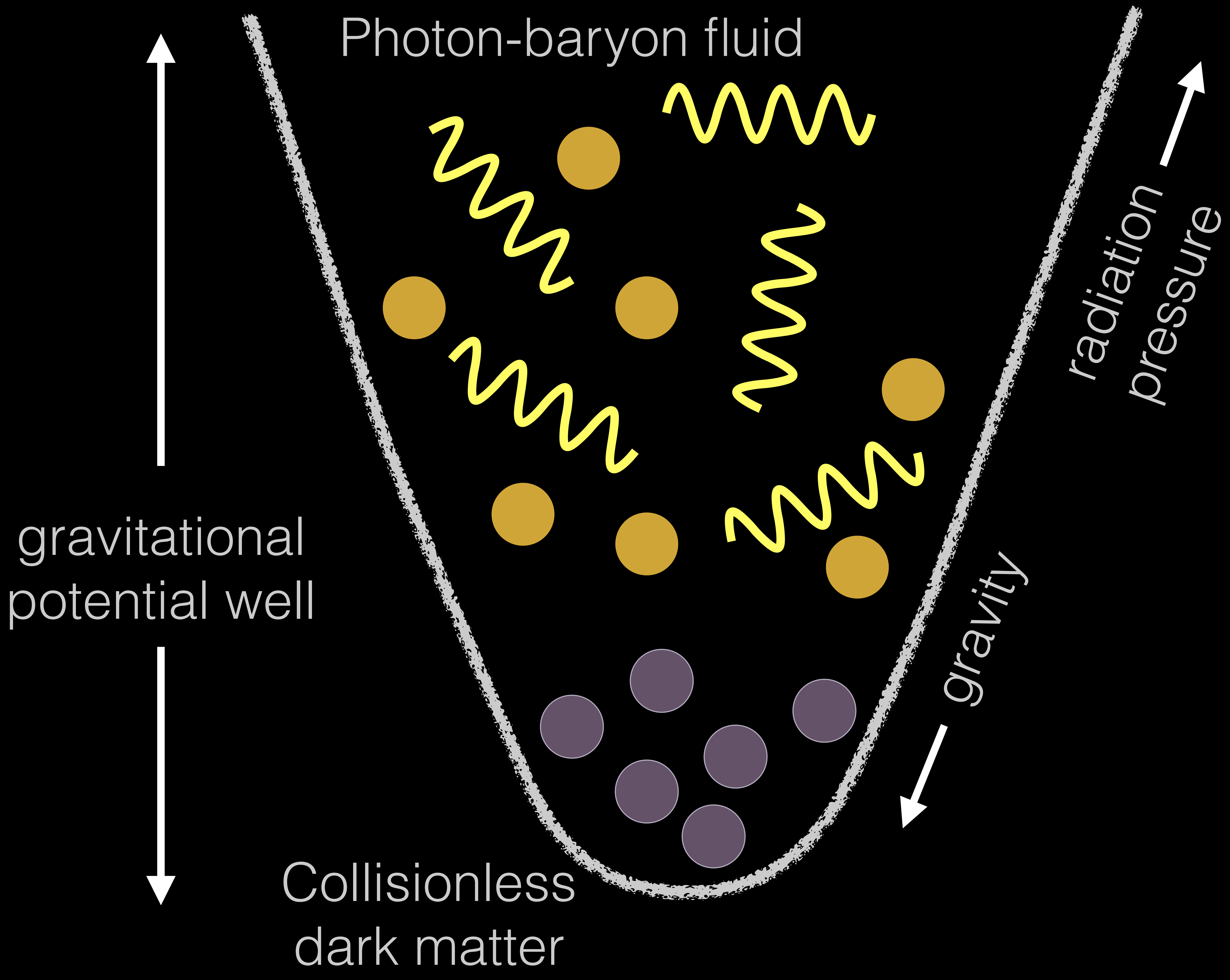


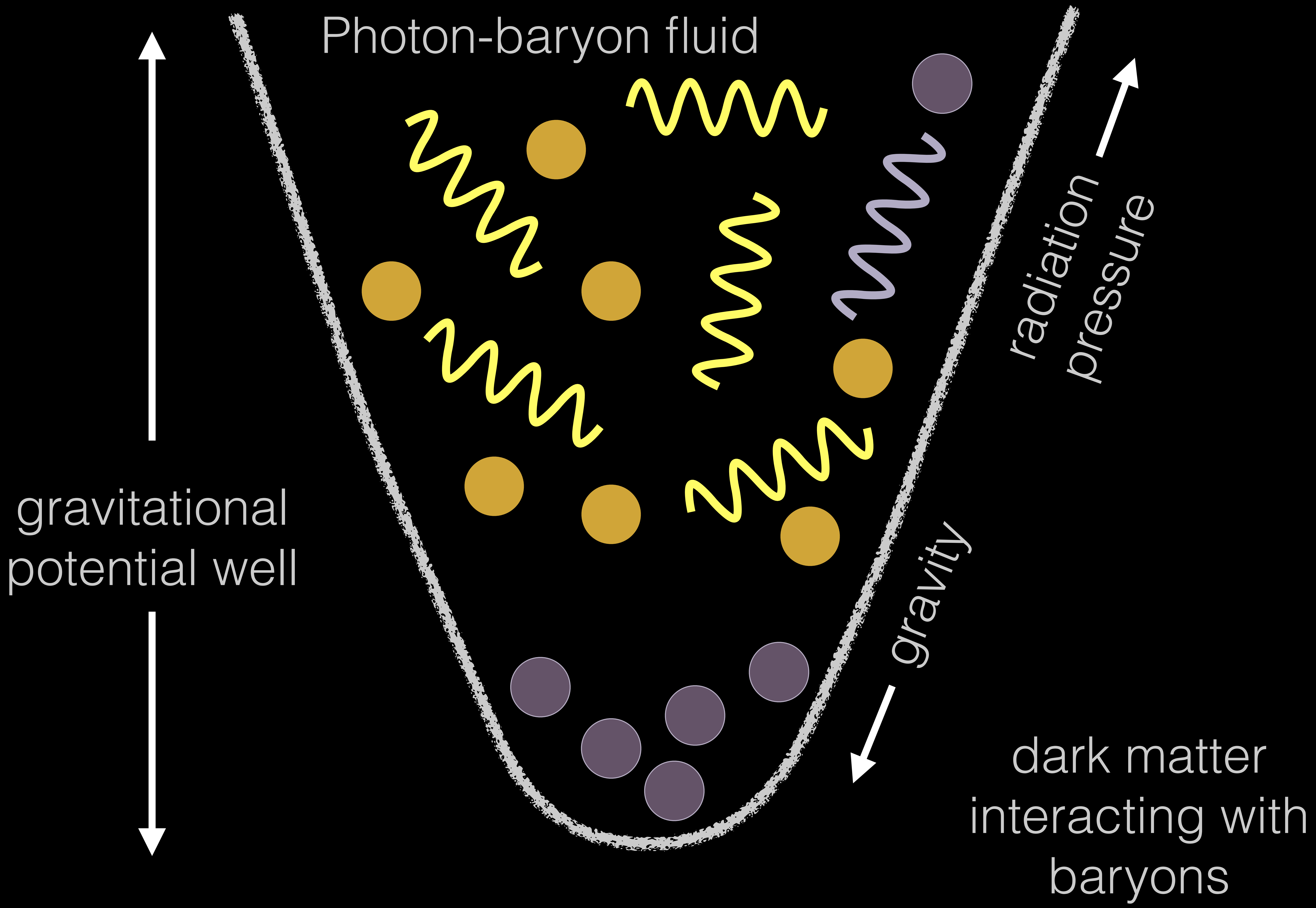




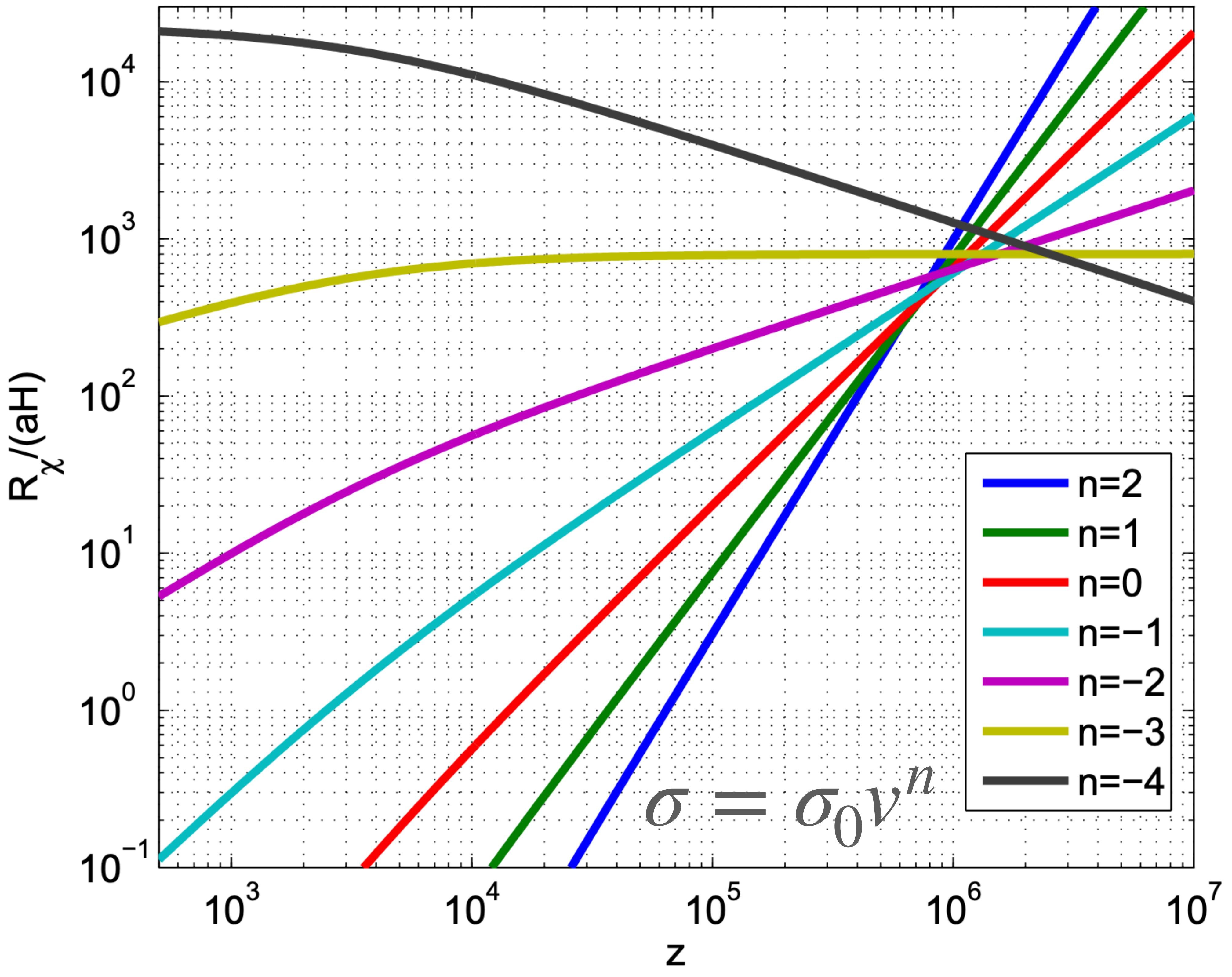


Rogers & Peiris

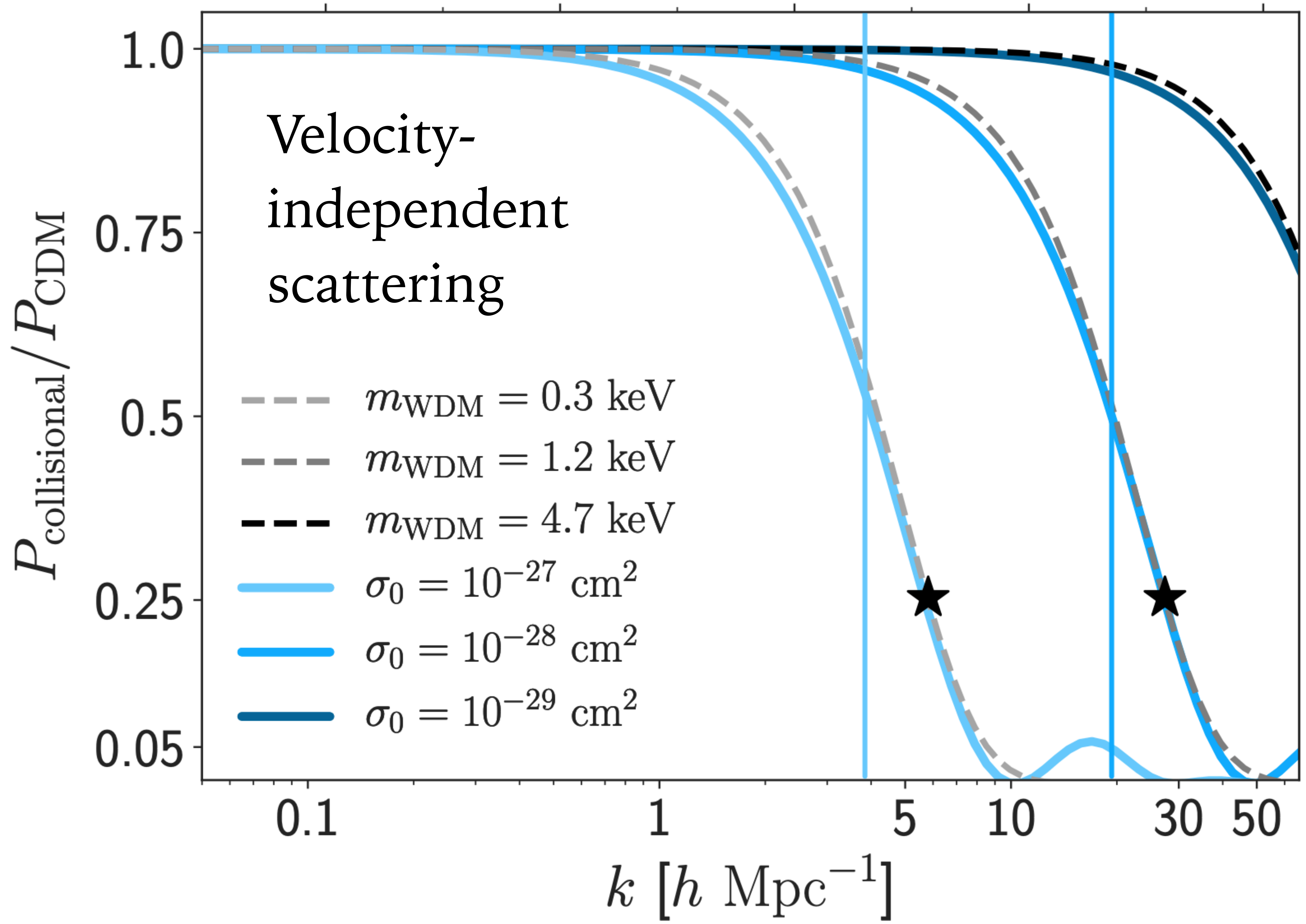

Photon-baryon fluid
radiation
pressure
gravity
gravitational
potential well
Collisionless
dark matter


Photon-baryon fluid
gravitational
potential well
radiation
pressure
gravity
dark matter
interacting with
baryons

DARK MATTER BARYON DRAG

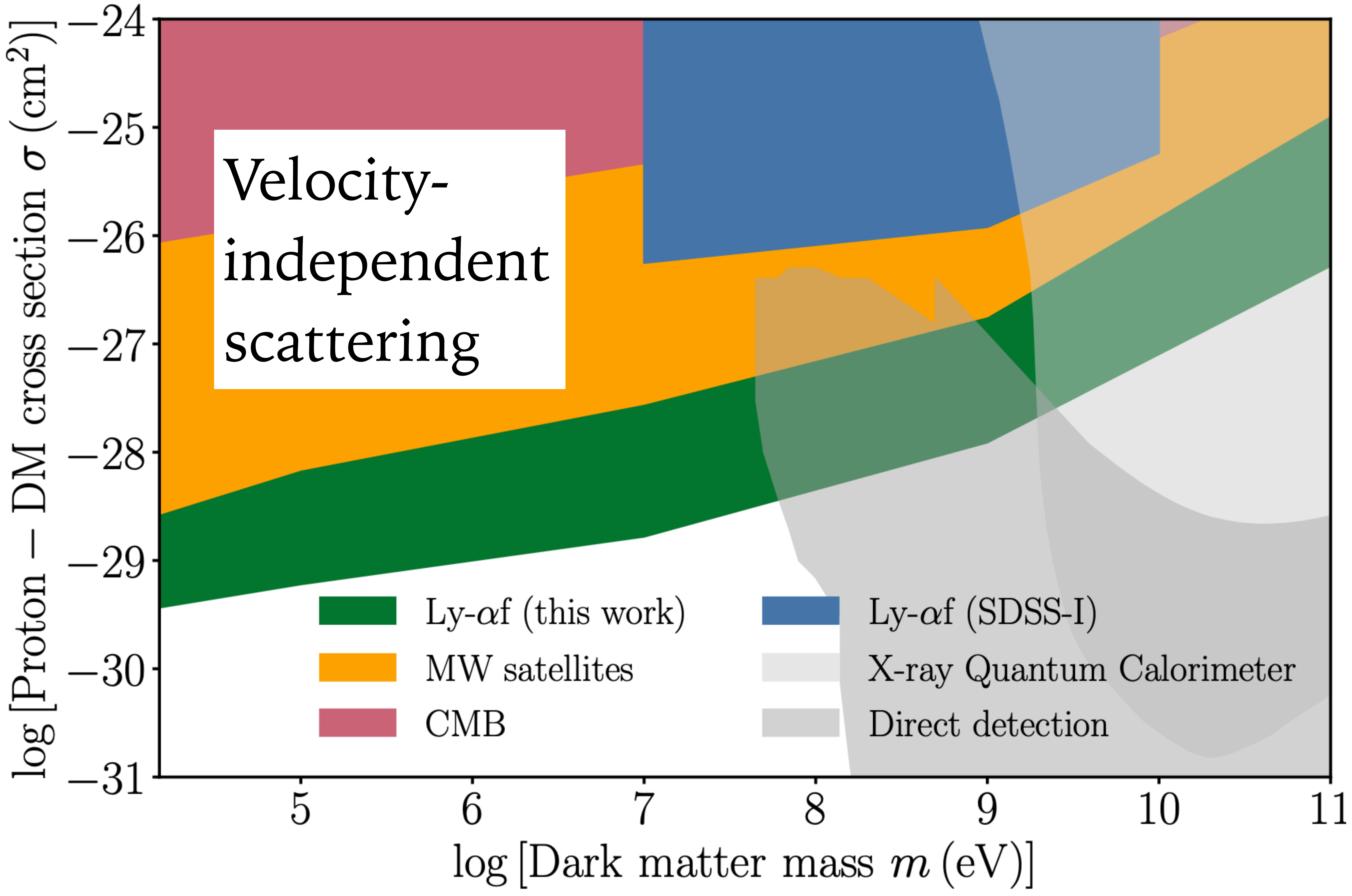


Dvorkin et al. (2014)

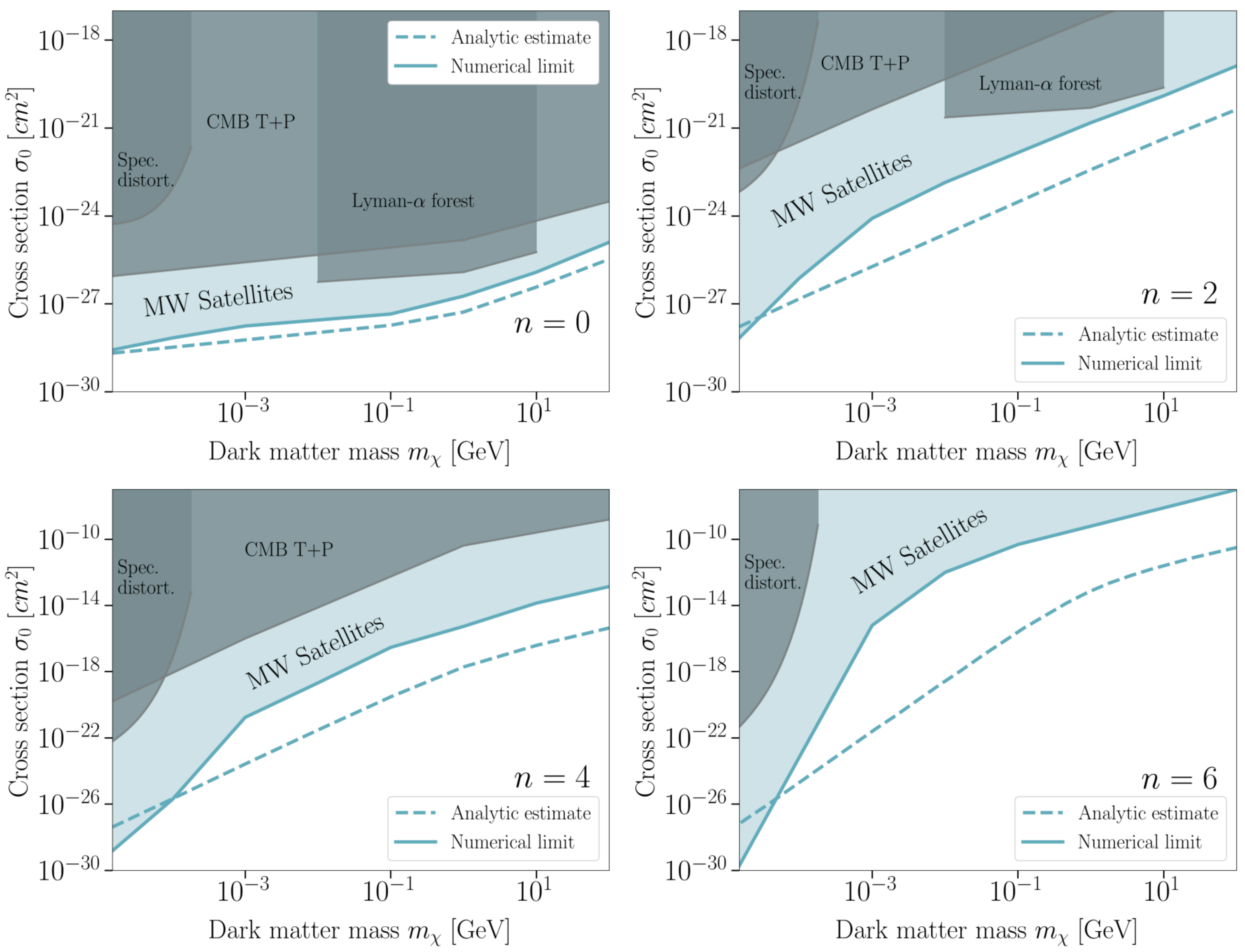


Nadler et al. (2020)

TESTING DARK MATTER BARYON SCATTERING WITH SUBHALOS AND LYMAN-ALPHA



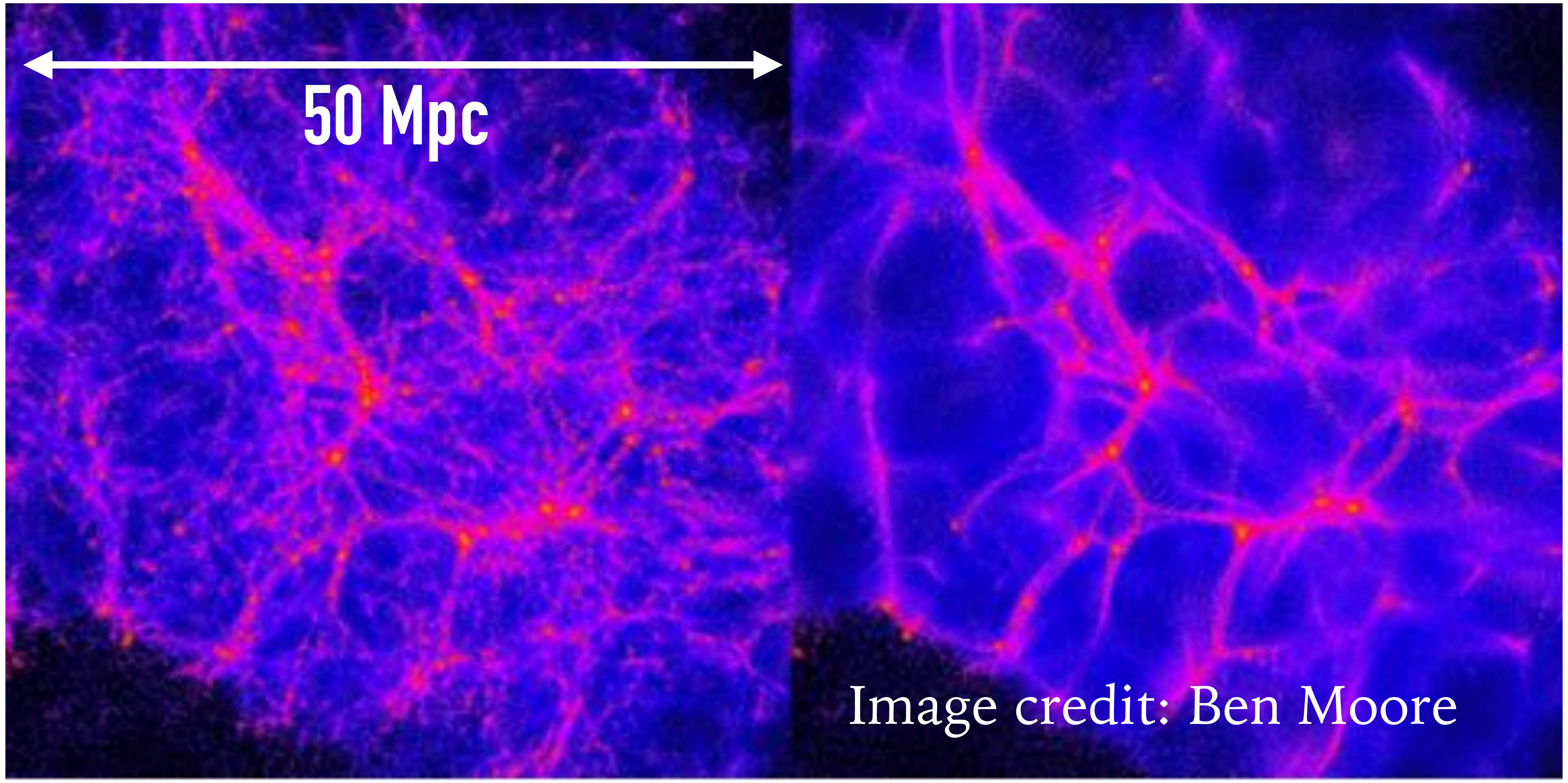
Rogers, Dvorkin, Peiris (2022)



Maamari et al. (2022)

VELOCITY EFFECTS ON HALOS (WARM DARK MATTER EXAMPLE)

Warm dark matter initial conditions: $$\Omega_\chi h^2 = \frac{m_\chi}{94\,eV}\frac{11}{4}\left(\frac{T_\chi}{T_\gamma}\right)^3$$



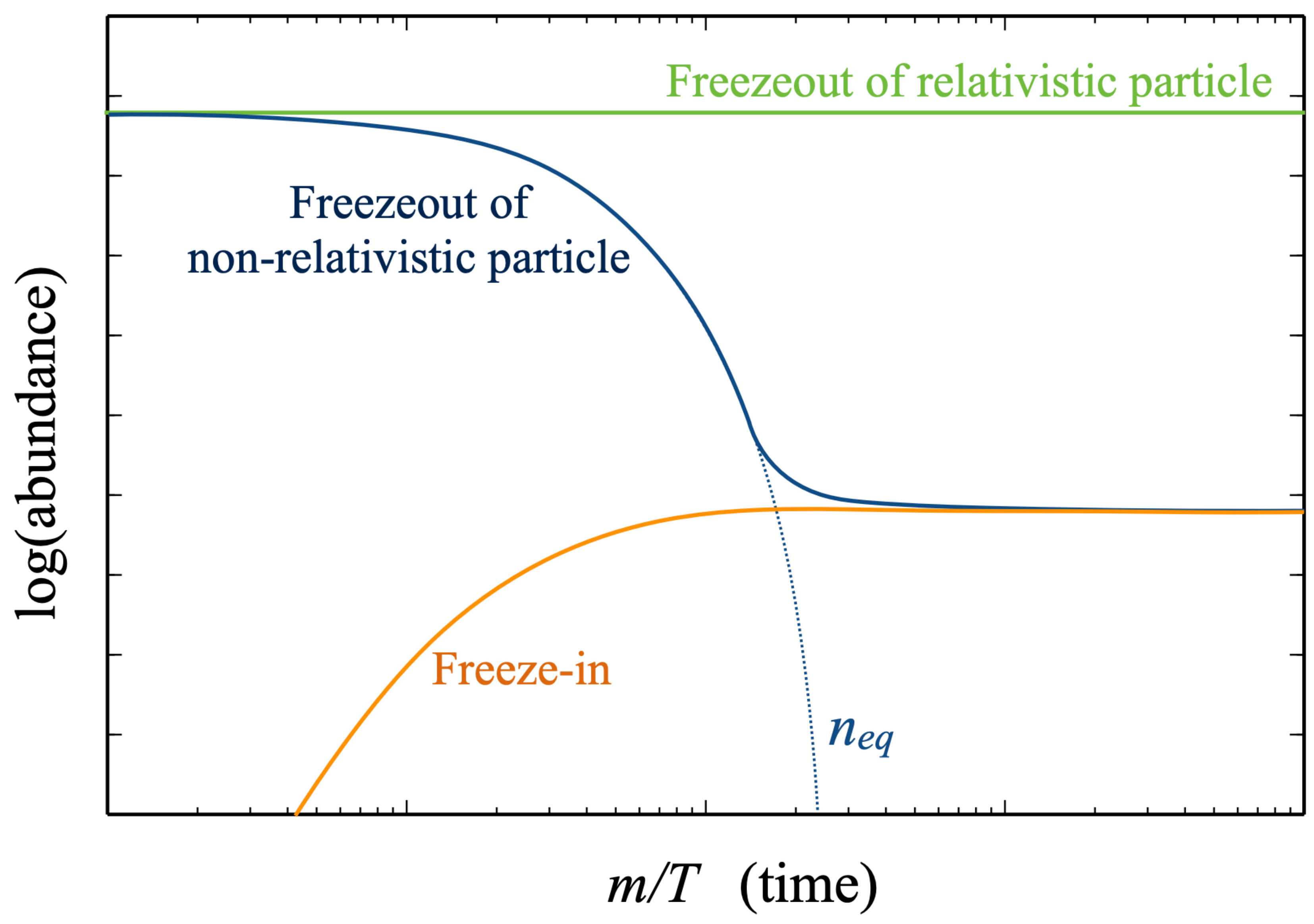
← Heavier, Cooler

Lighter, Hotter →

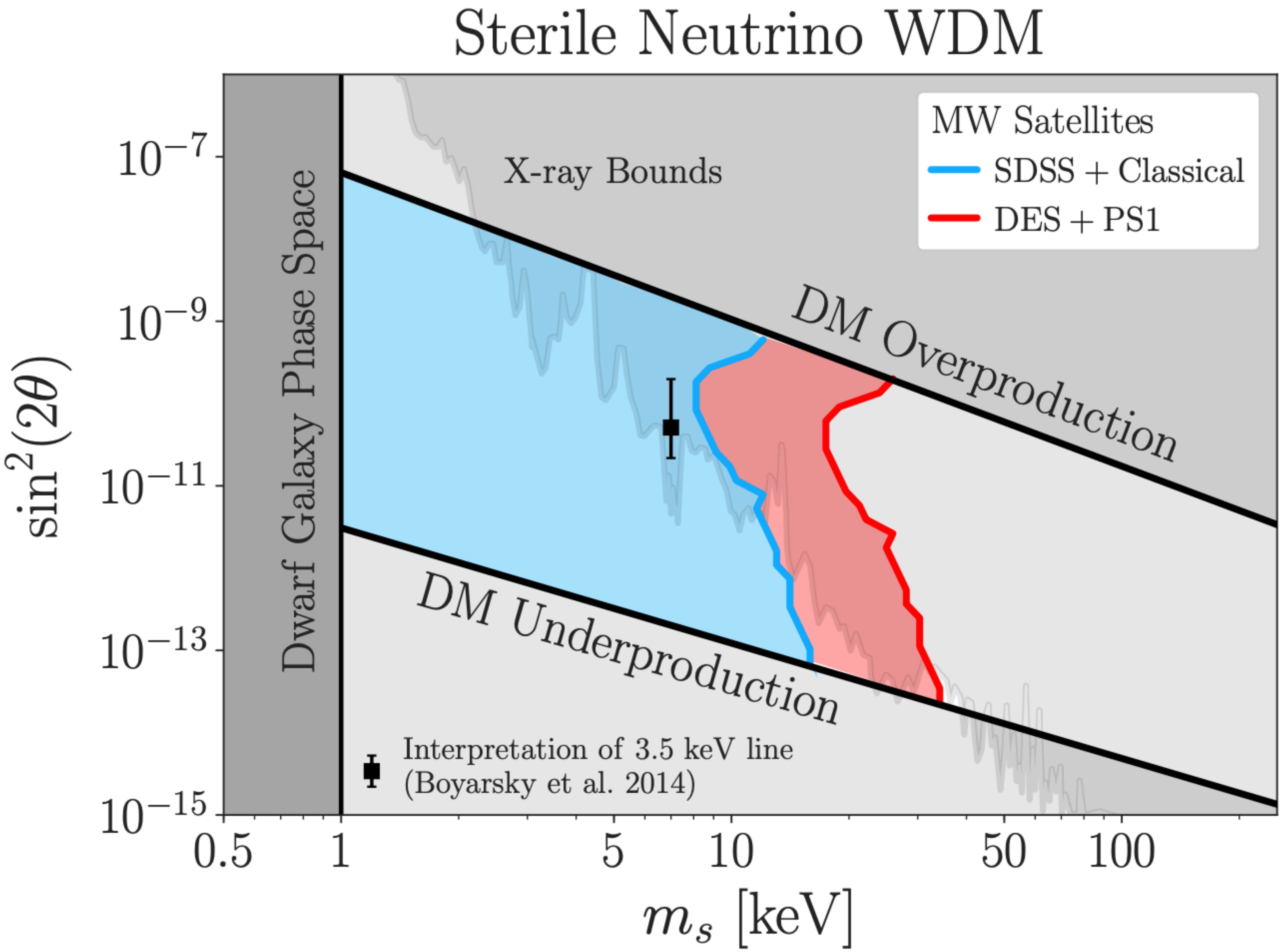
DECOUPLING WHILE RELATIVISTIC

Warm dark matter initial conditions: $$\Omega_\chi h^2 = \frac{m_\chi}{94\,eV}\frac{11}{4}\left(\frac{T_\chi}{T_\gamma}\right)^3$$

- ➤ Inspired by neutrino decoupling, this is the formula for any particle decoupling while relativistic
- ➤ Temperature ratio determined via entropy considerations, degrees of freedom in the bath
- ➤ For 5 keV-scale DM, there needs to be **~10,000 thermal degrees of freedom to dilute the temperature**! This benchmark model is probably not to be taken too literally (not a good idea to directly apply limits)
- ➤ Most analogous models are sterile neutrinos, subject to updated structure formation & x-ray constraints



From Tongyan's TASI lectures



DES collaboration (Nadler et al. 2020)